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SOLUBILIZATION AND MOVEMENT OF ORGANIC FORMS OF NITROGEN IN THE SOIL

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The occurrence of large fluctuations in the total nitrogen, ammonia, and nitrate contents of arable land has been recorded by Leather (20), Russell (27), Russell and Appleyard (29), Waynick (49), Waynick and Sharp (50), Lemmermann and Wichers (21), Clarke (8), Annett et al. (1), Smith (36), Thornton and associates (44, 45), Prescott and Piper (26), Batham and Nigam (5), Penman and Rountree (25), Bartholomew (4), Wilshaw (52), Sreenivasan and Subrahmanyan (40), and others. Prescott and Piper (26), Annett et al. (1), Sahasrabuddhe and co-workers (30–34), Wilshaw (52), and others have made attempts to correlate such fluctuations with seasonal variations and with other soil and cropping conditions. It has even been reported by Wilsdon and Ali (51), Annett et al. (1), Sahasrabuddhe and co-workers (30–34), Desai (11), Gerlach (14), Vandecaveye and Villanueva (46), Wilshaw (52), and others that under favorable conditions of moisture, temperature, aeration, and manuring, definite recuperation of nitrogen may proceed in soils.

In a recent communication, Sreenivasan and Subrahmanyan (41) have drawn attention to the effect, on such investigations, of certain external factors such as the normal variation in the composition of the soil from point to point in the field, uneven distribution of organic matter, erosion, silting, and movement of soluble nutrients.

It is generally believed that among the nitrogenous constituents of the soil, only the nitrates and, to a certain extent, ammonia are capable of movement from one stratum to another, as has been reported by Hall (15), Cook (9), Brown (7), Sahasrabuddhe and Gokhale (33), Shrikhande (35), and others. In the ordinary field soil, nitrates are present only in small quantities, and hence, their movement may not lead to any considerable change in the total nitrogen contents of different layers. Some evidence has been adduced by Sreenivasan and Subrahmanyan (43) to show that, in addition to the mineralized nitrogen, certain forms of organic nitrogen are also capable of movement through the soil and that this movement is influenced by the reaction of the soil and its soluble salt content. As further work on the nature and extent of such movement seemed desirable, the present inquiry was undertaken.

[1] The authors' grateful thanks are due to V. Subrahmanyan for his kind interest in the progress of this investigation.

EXPERIMENTAL

Solubilization of nitrogen during the decomposition of organic matter

The following preliminary experiments were carried out to determine the extent to which organic nitrogen is solubilized during the decomposition of complex nitrogenous materials in the soil. Finely powdered air-dry samples of rice straw (0.3 per cent nitrogen) and of pongam leaves (*Pongamia glabra*, 3.4 per cent nitrogen) and a commercial specimen of dried blood (12.3 per cent nitrogen) were mixed, in quantities corresponding to 25 mgm. N, with 100-gm. lots of a local virgin red loam soil, air dried, and passed through a 3-mm. sieve, and the mixtures maintained at 50 per cent saturation. With a view to finding out the peptizing effect, if any, of soluble salts, two more series were

TABLE 1

Changes in mineralized and total water- and salt-soluble nitrogen during the decomposition of organic matter in soil

Nitrogen in p.p.m. of soil

TREATMENT	AT START				AFTER 30 DAYS' DECOMPOSITION				AFTER 75 DAYS' DECOMPOSITION			
	Water extract		Saline extract		Water extract		Saline extract		Water extract		Saline extract	
	Mineralized N	Total N	Mineralized N	Total N	Mineralized N	Total N	Mineralized N	Total N	Mineralized N	Total N	Mineralized N	Total N
Soil alone (control)	5	12	8	14	8	14	10	18	14	19	18	22
Soil + rice straw	8	51	6	37	8	58	12	44	22	58	29	62
Soil + dried blood	16	58	21	62	109	151	142	174	107	154	145	177
Soil + pongam leaf	18	65	23	..	59	84	94	86	66	98	85	101
Soil + pongam leaf + NaCl	18	55	..	..	95	105	...	...	81	112	...	...
Soil + pongam leaf + CaO	15	55	23	56	82	106	96	104	78	90	89	98

started by mixing 200 mgm. each of sodium chloride and lime with 100-gm. lots of the soil before treatment with pongam leaves in the manner described above. The mixtures, in 250-cc. conical flasks, loosely plugged with cotton wool, were incubated at 30° and allowed to decompose. The contents of the flasks were examined at the start and at the end of 30 and 75 days' decomposition respectively for (*a*) mineralized ($NH_3 + NO_3$) nitrogen and (*b*) total water- or salt-soluble nitrogen. One set of mixtures during each sampling was extracted by shaking with 200 cc. of water for 90 minutes and filtered, and another set was extracted with a similar quantity of a 2 per cent aqueous solution of NaCl for the same period before filtering. The mineralized nitrogen in an aliquot of the filtrate was determined in each case by distillation with

magnesia and Devarda's alloy (2), and the total nitrogen in another aliquot was determined by the usual Kjeldahl method after preliminary reduction of nitrates (38). The results are given in table 1.

It may be seen (table 1) that with the progress of decomposition, appreciable amounts of organic nitrogen are peptized in the different samples. A part of this nitrogen undoubtedly is being rapidly mineralized while it is being solubilized, and consequently the quantities of water- and salt-extractable nitrogen present in the system at any one time are generally small. In the presence of lime, the water extract gives a lower figure for peptized nitrogen; this is perhaps only to be expected, since lime flocculates some of the organic nitrogen in solution. There is not much difference in the water-soluble nitrogen due to the presence of sodium chloride in the mixture. Likewise, the differences between corresponding values for water- and salt-soluble nitrogen are only slight. For mineralized nitrogen, the higher values obtained in the saline extract as compared with those in the water extract are due to the greater extraction of the adsorbed ammonia from the soil.

Effect of swamping the soil on the solubilization of nitrogen

With a view to observing the comparative rates of solubilization of organic nitrogen under arid and swamp soil conditions, some experiments were carried out in which 100-gm. lots of the soil were treated with different organic materials in quantities corresponding to 60 mgm. of nitrogen. The substances employed were dried blood, lantana leaf powder (*Lantana camara* Linn., 2.2 per cent nitrogen), and pongam seed cake (3.4 per cent nitrogen). In one set of experiments, the mixtures were kept as before at 50 per cent saturation capacity; in the other set, they were swamped with 100 cc. of water before being incubated at 30°. The changes in the different forms of water-soluble nitrogen and in total nitrogen were followed in each case for 2 months at intervals of 20 days from the start. Total nitrogen in the samples was determined according to the method outlined by Sreenivasan (37) and by Sreenivasan and Subrahmanyan (39); and ammonia, nitric, and total nitrogen in aliquots of the filtrates obtained after extraction of the soil suspensions with 200 cc. of water were all determined according to the methods of the A. O. A. C. (2). For total nitrogen determinations, nitrate was first reduced in alkaline medium (38). The water-soluble organic nitrogen is the difference between the total and the mineralized water-soluble nitrogen. The results are recorded in table 2.

The general observations in regard to the rates of decomposition of the different materials and the losses in total nitrogen are similar to those recorded by earlier workers (18, 41, 42).

It is well known that in the swamp soil, transformations of added organic nitrogen stop at the ammonia stage and that nitrification does not take place until the initial fermentation subsides and aerobic conditions are restored.

TABLE 2

Changes in water-soluble and total nitrogen under moist and swamp soil conditions

Nitrogen in p.p.m. of soil

TREATMENT	AT START				AFTER 20 DAYS' DECOMPOSITION				AFTER 40 DAYS' DECOMPOSITION				AFTER 60 DAYS' DECOMPOSITION			
	Water-soluble N			Total N	Water-soluble N			Total N	Water-soluble N			Total N	Water-soluble N			Total N
	NH_3-N	Nitric N	Organic N		NH_3-N	Nitric N	Organic N		NH_3-N	Nitric N	Organic N		NH_3-N	Nitric N	Organic N	
Moist Series																
Soil alone (control)	7	9	27	575	9	18	30	578	7	18	12	545	7	22	6	540
Soil + dried blood	11	7	75	1,175	46	49	30	1,104	77	65	32	1,028	55	80	29	940
Soil + oil cake	7	7	87	1,179	37	15	51	1,132	62	31	9	1,059	47	49	9	994
Soil + lantana leaf	5	11	49	1,165	11	11	36	1,165	28	28	6	1,095	19	36	11	1,050
Swamped Series																
Soil alone (control)	7	11	29	571	11	11	28	579	16	6	5	516	11	11	13	520
Soil + dried blood	11	7	86	1,168	29	14	43	1,084	69	12	44	997	60	44	37	886
Soil + oil cake	10	7	91	1,170	23	9	60	1,100	56	11	22	1,038	52	28	20	960
Soil + lantana leaf	9	10	50	1,162	7	11	40	1,140	9	15	12	1,060	11	26	15	1,013

TABLE 3

Effect of sodium chloride on changes in water-soluble and total nitrogen

Nitrogen in p.p.m. of soil

TREATMENT	OCTOBER 15, 1937 (AT START)				NOVEMBER 5, 1937				NOVEMBER 28, 1937				DECEMBER 18, 1937				JANUARY 6, 1938			
	Water-soluble N			Total N	Water-soluble N			Total N	Water-soluble N			Total N	Water-soluble N			Total N	Water-soluble N			Total N
	NH_3-N	Nitric N	Total N		NH_3-N	Nitric N	Total N		NH_3-N	Nitric N	Total N		NH_3-N	Nitric N	Total N		NH_3-N	Nitric N	Total N	
Soil alone (control)	6	9	17	575	5	12	24	576	4	9	28	557	11	11	43	548	13	6	37	532
Soil + NaCl	7	12	21	566	7	8	25	566	5	16	32	548	6	6	36	536	15	3	43	519
Soil + lantana leaf	9	6	58	1,181	13	12	48	1,194	12	19	49	1,175	16	70	120	1,160	6	57	104	1,100
Soil + lantana leaf + NaCl	16	6	52	1,174	18	6	47	1,160	22	6	44	1,143	14	8	65	1,121	15	12	63	1,048
Soil + dried blood	16	9	67	1,186	115	22	151	1,093	61	134	229	1,049	48	155	244	998	34	84	177	960
Soil + dried blood + NaCl	23	12	58	1,185	101	11	154	1,065	66	32	121	1,005	79	29	151	944	45	22	102	924

Consequently, most of the mineralized nitrogen, especially in the initial stages of decomposition, is present in the system as ammonia and is held adsorbed by the soil colloidal complex. Hence, the inorganic nitrogen and the total water-soluble nitrogen in the flooded series (table 2) are always much less than the corresponding values in the moist series where most of the mineralized nitrogen exists as the readily extractable nitrate. Although the total water-soluble nitrogen is less in the swamped series than in the moist series, it may be observed that the water-soluble organic nitrogen is in almost all instances more than that in the corresponding moist series. Again, since the losses in total nitrogen are more pronounced in the flooded series [cf. also Harrison and Aiyer (17, 18)], the percentage of the total nitrogen present in water-soluble organic forms will be even more in these cases.

Influence of sodium chloride on the dissolution of organic nitrogen in the soil

The presence of small amounts of sodium chloride in the soil does not lead to the peptization of appreciably larger quantities of organic nitrogen (table 1). The following further experiments on the effect of addition of sodium chloride in small amounts were carried out. A number of shallow glazed earthenware pots were filled with 2-kgm. lots of the sieved air-dry soil. Dried blood and lantana leaves in quantities corresponding to 60 mgm. of nitrogen for every 100 gm. of soil were thoroughly incorporated into the soil in the different pots, and the mixtures were allowed to decompose under field conditions after their moisture contents had been raised to about 30 per cent of the weight of the soil. A control series with untreated soil was included. In one set of pots, the soil was also mixed thoroughly with 4 gm. of sodium chloride per pot before the addition of the organic materials. The changes in the different forms of water-soluble nitrogen and in total nitrogen were then followed in aliquot samples, as before, at periodic intervals. Table 3 gives the results obtained.

It may be noted that the presence of sodium chloride results in significant differences in the rate and extent of decomposition as measured by the formation of mineralized and organic water-soluble nitrogen and the changes in total nitrogen. Thus, in the presence of salt, the mineralization of added organic matter is less than in its absence. In particular, nitrification is greatly hampered in these cases obviously because of the less open texture brought about by the sodium ion. This results in greater accumulation of ammonia, especially in the later stages; and the soil, being also rendered alkaline in character by the sodium ion, volatilization of the ammonia follows. A greater loss in total nitrogen is therefore observed in all the sodium chloride-treated series.

Sodium chloride was observed to peptize more of the organic matter, since the water extracts in such cases were always darker in color and, besides, gave higher figures for total carbon as estimated in a few cases by the method described by Bhaskaran et al. (6). But it would appear that with sodium chloride, more of the carbon than of the nitrogenous compounds were brought into solution. Hence, water-soluble organic nitrogen was never significantly

different in these series from the values obtained in the series without sodium chloride. This may also be due to the greater losses in total nitrogen in the saline than in the corresponding control series.

Distribution and movement of different forms of organic nitrogen in the soil

Although the lateral and downward movement of soluble nitrogenous fertilizers, particularly of ammonia and nitrates in the soil has been studied by a number of workers no information is yet available regarding the possible movement of the humic organic nitrogen of the soil under similar conditions. It was therefore thought desirable to study the nitrogen content of the soil organic matter at different depths and during the decomposition of organic matter added to the surface layers.

In the following experiments, a number of cylinders (10 inches in height by $3\frac{1}{2}$ inches in diameter) made of thick paraffined paper were filled to a height of 9 inches with soil. The cylinders were stood in glass dishes of slightly greater diameter, and additional stability was given to the soil columns thus obtained by placing them in rows in a wooden chest with a frame for each. The soil, which was the air-dried loam used in the earlier studies, was brought to a moisture content of 30 per cent before being poured into the cylinders. Five sets of treatments were given as follows: (I) Soil, unmanured, control; (II) Soil with top 2 inches (about 250 gm.) thoroughly admixed with pongam leaf powder, equivalent to 60 mgm. of nitrogen; (III) same as (II) but the entire soil was mixed with 0.3 per cent sodium chloride before incorporation of the organic matter in the surface 2 inches; (IV) and (V), same as (II) but the soil was previously adjusted to pH 8.0 and 4.6 respectively by addition of the necessary amounts of dilute alkali and acid respectively.

The cylinders of soil columns thus made could be easily cut at any depth or depths desired, by means of a sharp metal plate, preventing, thereby, any mixing of the soil with other layers. At the beginning of the experiment and at intervals of one month thereafter, one cylinder from each series was removed for analysis. The cylinders were cut at depths of 2, 4, and 6 inches from the top; thus, four samples from successive depths were obtained each time. These samples were analyzed separately for mineralized ($NH_3 + NO_3$) nitrogen, total nitrogen, and the different fractions of organic nitrogen according to the scheme of Page and his co-workers (23, 24). The results are given diagrammatically in figures 1 to 5.

Changes in mineralized nitrogen. In the control series, the figures for mineralized nitrogen remained rather steady throughout the period of experimentation, nor was there any appreciable change in the values at different depths. In the second series it was noted that with the progress of decomposition considerable mineralized nitrogen accumulated in the lower layers, especially to a depth of 6 inches. This is significant in view of the fact that the leaf material was mixed only with the first 2 inches of the soil; there is thus definite evidence of a downward movement of the inorganic nitrogen. In the third

series, in which the soil was mixed with sodium chloride before the organic matter was added to the surface 2-inch layer, mineralization was confined mostly to the surface soil. Downward movement was not much in evidence, the figures for the second and subsequent layers being about the same as those for the unmanured control soil (series I). It was observed that the soil in the third series had become somewhat sticky and, in consequence, was not quite permeable. Similar results were obtained in the fourth series where the green manure was allowed to decompose in the surface layer of soil previously

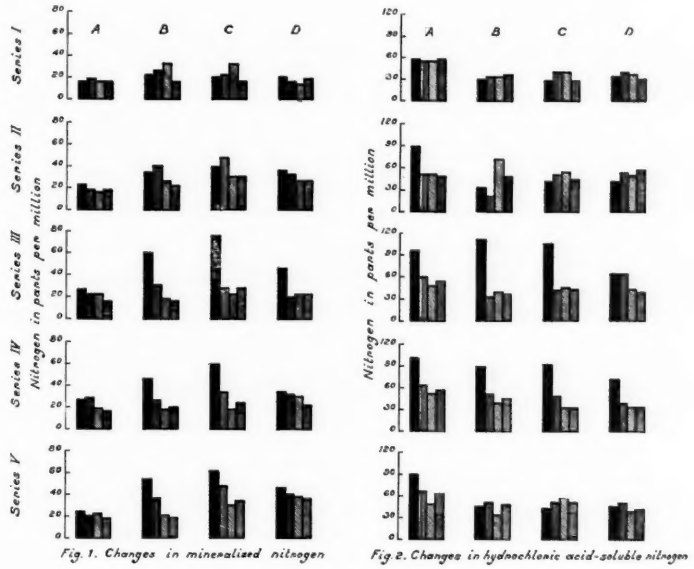

Fig. 1. Changes in mineralized nitrogen

Fig. 2. Changes in hydrochloric acid-soluble nitrogen

adjusted to pH 8, but mineralization was less rapid here, and percolation was slightly better. The low values for mineralized nitrogen even at the end of 4 months may also be due to some loss of ammonia due to the alkaline reaction of the soil. In the fifth series with soil adjusted to pH 4.6, ammonification in the surface layers was good. This was followed, as in series II, by a certain amount of movement of mineralized nitrogen into the lower layers.

Changes in hydrochloric acid-soluble nitrogen. In the control series, the values for HCl-soluble nitrogen fell rapidly during the first month as a result of conversion into other probably mineralized forms; the figures then remained nearly steady. In the manured series, there was a definite penetration of the

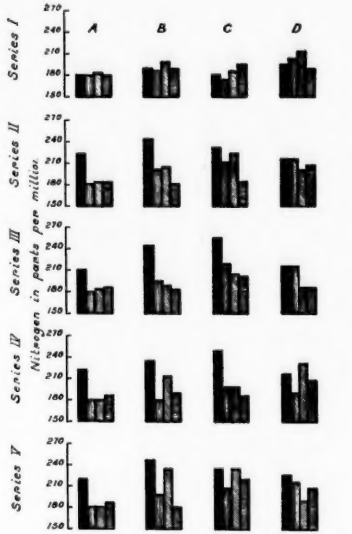

Fig. 3. Changes in alkali-soluble nitrogen

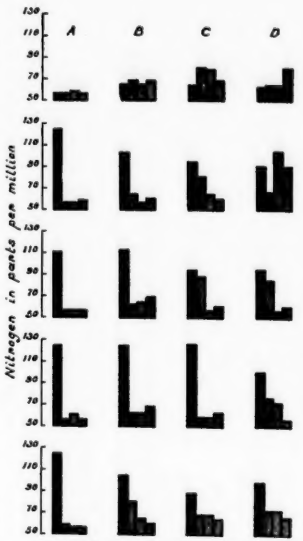

Fig. 4. Changes in alkali-soluble and acid-insoluble nitrogen

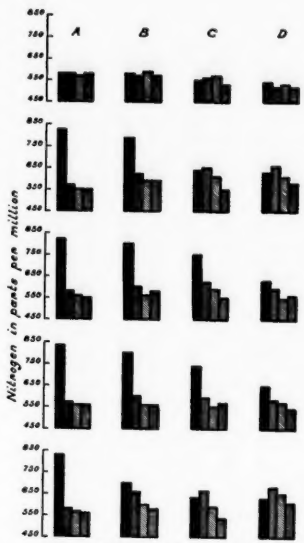

Fig. 5. Changes in total nitrogen

A) Sample taken at commencement. ■ 0 to 2 inches soil
B) " " after 1 month. ■ 2 " 4 " "
C) " " " 2 months. ■ 4 " 6 " "
D) " " " 4 " ■ 6 " 8 " "

Series I to V represent treatments as given in text.

acid-soluble nitrogen into the lower layers with the progress of decomposition. This form of nitrogen appeared to bear some relationship to the inorganic nitrogen in the different layers. In the saline soil, there was an accumulation in the surface layer during the first 2 months, followed by a slight movement to the lower layers. With the alkaline soil, more or less similar results were obtained, but no appreciable movement was evident. In the acid soil, the results were again similar to those in series II.

Changes in alkali-soluble nitrogen. Alkali-soluble nitrogen increased slightly with time even in the control series, probably because of fresh decomposing organic matter which the soil might have contained. In the manured series, there is, on the whole, an increase in alkali-soluble nitrogen. This is most pronounced in the first month of decomposition. Movement of alkali-soluble nitrogen from the surface to the lower layers is also definite and appreciable. The effects due to salt content of the soil or to changes in reaction are not very noticeable.

Changes in alkali-soluble and acid-insoluble nitrogen. In the unmanured control series, there was a slight increase, of about 20 per cent, in the value for alkali-soluble and acid-soluble nitrogen at the end of 4 months. The soil, taken from an uncultivated tract of land, obviously contained, at the time of sampling, some decomposing organic matter, which probably accounts for the observed increase in this form of nitrogen. In the manured series, a slight decrease in the surface soil was followed by a definite increase and downward movement. Similar results were obtained with the acid soil (series V). With the saline and alkaline soils (series III and IV), downward movement in this form of nitrogen was slight, penetration being confined, at best, to the first two layers.

Changes in total nitrogen. In the control soil, there was a slight loss in total nitrogen content at the end of 4 months; otherwise, the values remained nearly steady and were about the same in the different layers. In all the manured series, movement from the surface to the lower layers was evident. There was also a progressive loss in total nitrogen in these cases. In the saline and alkaline soils, the movement was less and the loss more than in the neutral and acid soils.

Changes in insoluble humin and in resistant nitrogen. The insoluble humin, of Page and co-workers (23, 24), was calculated for the four layers of the different series and at the various stages of decomposition by subtracting from the values for total nitrogen, the corresponding figures for acid- and alkali-soluble nitrogen. The values are given in table 4. Resistant nitrogen was determined independently in the soil samples according to the scheme of proximate analysis worked out by Waksman and Stevens (48). This represents the nitrogen in the residue after boiling with 5 per cent sulfuric acid for 6 hours [cf. also Duthie (12)]. The figures are included in table 4.

In the control series, the values for resistant nitrogen remain fairly steady in the topsoil and subsoil layers during the first 2 months, but at the end of 4

months, there is a fall in this constituent. In series II and V, a definite movement from the surface down to the subsoil layers is noted. In fact, the resistant nitrogen in the second or third layer of the soil is generally more than that in the surface 2 inches. It may be noted in this connection that Duthie (12) has also observed an increase in resistant protein of certain soil profiles with depth. With the saline and alkaline soils (series III and IV), however,

TABLE 4

Changes in "humin" and "resistant" nitrogen

Nitrogen in p.p.m. of soil

TREATMENT	DEPTH	JUNE 25, 1937		JULY 26, 1937		AUGUST 26, 1937		NOVEMBER 1, 1937	
		Humin N	Resistant N	Humin N	Resistant N	Humin N	Resistant N	Humin N	Resistant N
	inches								
I. Control (untreated soil)	0–2	339	317	364	327	344	345	313	308
	2–4	339	319	350	305	344	352	279	287
	4–6	...	...	359	309	345	340	276	272
	6–9	...	...	344	324	301	360	301	274
II. Soil + green manure	0–2	513	362	508	346	365	329	368	306
	2–4	338	316	401	352	390	368	387	342
	4–6	...	...	315	362	331	310	359	320
	6–9	...	...	360	342	317	312	317	296
III. Soil + NaCl + green manure	0–2	515	375	461	364	389	325	355	296
	2–4	338	319	369	341	351	329	316	300
	4–6	...	...	332	307	342	329	321	296
	6–9	...	...	363	296	305	313	334	275
IV. Soil (pH 8.0) + green manure	0–2	509	477	410	355	401	379	359	326
	2–4	326	300	364	330	342	324	355	308
	4–6	...	...	318	336	319	307	312	208
	6–9	...	...	328	308	348	312	305	278
V. Soil (pH 4.6) + green manure	0–2	515	380	410	370	360	309	356	308
	2–4	328	348	409	364	404	371	410	362
	4–6	...	...	329	308	310	329	368	324
	6–9	...	...	353	302	268	275	314	279

there is a general fall in the values for resistant nitrogen toward the lower layers; such a decrease in resistant protein has been considered to indicate soil deterioration (12).

The changes in insoluble "humin" nitrogen and in resistant nitrogen did not appear to be related in any manner. There was a general decrease in "humin" nitrogen with the progress of decomposition in all cases, whereas the variation between different layers, even in the neutral and acid soils (series II and V), were irregular in many instances. On the other hand, the resistant nitrogen

did not change much as a result of progressive decomposition of the leaf material, and it appeared probable that this constituent measured a more definite form of nondecomposable organic nitrogen of the soil than did the "humin" nitrogen.

DISCUSSION

The results have shown that in the soil and during the decomposition of organic residues, there is appreciable solubilization of some forms of organic nitrogen, which may, under favorable conditions of texture and reaction, steadily move from one stratum to another. There have been numerous investigations on the study of the nature of the soil organic matter and of the relations between carbon and nitrogen in regard to the origin, nature, mode of formation, and fractionation of soil humic matter (47). Recent researches have also indicated that in temperate climates, the ratio of carbon to nitrogen diminishes significantly with depth of the soil within a profile (16, 22). In other words, there is a proportionately larger amount of nitrogenous complexes than of carbohydrate complexes present in the subsoil layers (12). Besides, Arnold and Page (3) find that the subsoil contains a type of humus which is more readily soluble in cold alkali than is the organic matter of the surface soil, and hence they conclude that the organic matter in the subsoil was not formed *in situ* as a result of decomposition, but was washed down from the surface soil. According to Crowther (10), nitrates and other nutrients in Rothamsted soils are stored to a considerable extent with the water in the subsoil structural units.

Russell (28) also observes that the soil reaction is an important factor determining accumulations of organic matter in the surface of soils or its mingling with the other layers. Earthworms are another important agency, especially in temperate and subtropical countries, in mixing up the soil constituents, dragging in leaves and other organic residues from the surface and thus facilitating decomposition by the microorganisms.

Although the solubilization and movement of organic nitrogen at any one time may be comparatively slight, yet, repeated action, especially during months of heavy and continuous rainfall, may carry down a considerable portion of the organic nitrogen to the lower strata of the soil. During dry weather, the decomposed organic residues of the subsoil may be carried up to the surface layers through capillary action. Such movements, as have been already pointed out by Sreenivasan and Subrahmanyan (43), may profoundly affect the nature and extent of fluctuations in the nitrogen contents of soils with seasonal variations. Their significance in relation to conservation and availability of soil nitrogen remains obscure. Mere surface analyses of soils in regard to supply of available nutrients will not be sufficient, therefore, for the evaluation of the fertility status of soils and may, indeed, often be misleading. Further work on the extent to which the plant draws upon the subsoil for its needs is therefore highly desirable.

SUMMARY

The changes in mineralized and total water-soluble nitrogen during the decomposition of organic materials such as dried blood, green manure, and seed cake in the soil have been followed. It is found that solubilization of organic forms of nitrogen is appreciable in the different cases. Lime flocculates a part of the organic nitrogen in solution.

The quantities of organic nitrogen brought into solution during the decomposition of organic matter in the soil are greater under swamp soil conditions than in moist soil. Under flooded conditions, there is also a greater loss in total nitrogen from the system, and hence the proportion of water-soluble or peptized organic nitrogen is even more in such cases.

In the presence of sodium chloride, increase in water-soluble organic nitrogen in the soil is slight, but loss of total nitrogen is more.

Study of the changes in mineralized and total nitrogen and in the different fractions of organic nitrogen through successive layers of soil of which only the surface 2 inches was mixed with green manure has revealed that, during decomposition, there is considerable movement of the different forms of nitrogen from one stratum to another. The extent of such movement, determined mainly by the texture and reaction of the soil, is less pronounced in saline and alkaline soils than in acid or neutral soils.

The significance of such movements in relation to the periodic fluctuations in soil nitrogen and to the supply of available nutrients from the subsoil, has been indicated.

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POSSIBLE LOSSES OF NITROGEN FROM ACID SOILS THROUGH THE DECOMPOSITION OF NITRITES

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It is generally accepted, as a result of extensive studies on nitrification,[1] that the organic nitrogen of the soil is converted by organisms first to ammonia, then to nitrites, and next to nitrates. Nitrites may be decomposed by denitrifying organisms with some evolution of free nitrogen. Temple (4) reported that nitrites were rapidly decomposed in an acid soil with formation of N_2O_3, which was detected by its odor. Turtschin (5) has recently reported that acid soils react with nitrites, with consequent losses of nitrogen in the form of gaseous nitrogenous compounds. Many soils do not nitrify ammonium sulfate well without additions of calcium carbonate (2). The question arises as to whether this is really a failure to nitrify or whether nitrites are produced and then decomposed, with consequent loss of nitrogen. In the latter event, serious losses might occur in some soils. The work here presented is a study of this problem.

PRELIMINARY WORK

In the preliminary work, 36 soil samples were selected from seven different counties of Texas, representing a variety of soil types. They were acid to almost neutral in reaction, with pH values of 4.4 to 6.9. The soils were first tested to determine whether they decompose nitrites. The soil mixtures were prepared in duplicate, by the use of 100 gm. of soil, 10 cc. sodium nitrite solution containing 10 mgm. nitrogen (equal to 100 p.p.m.), and enough water to equal 50 per cent of the water capacity of the soil. Similar mixtures were prepared with the further addition of 1 gm. of calcium carbonate. They were incubated for 2, 4, and 8 days at 35°C. Portions equivalent to 20 gm. of dry soil were then taken and nitrates and nitrites determined by the usual method (1).

At the end of the period, the quantity of nitrates had increased, and the quantity of nitrites had decreased. The net losses of nitrogen were determined by subtracting the average amounts of nitrate and nitrite nitrogen found at the end of the incubation period from the amounts of nitrous nitrogen added to each culture plus the amounts of nitric nitrogen found in the original soil.

[1] Since Waksman (6) gives many references, a lengthy bibliography is not cited here.

When calcium carbonate was not added, the average loss of nitrogen was 47 p.p.m. (equal to 47 per cent of the nitrite nitrogen added) in the first 2 days,

TABLE 1

Loss of nitrogen in 8 days from soil containing 100 p.p.m. of nitrites, with and without calcium carbonate

Results in parts nitrogen per million of soil

TYPE OF SOIL	DEPTH	pH OF ORIGINAL SOIL	LOSS OF NITROGEN	
			Without calcium carbonate	With 1 per cent calcium carbonate
	inches		*p.p.m.*	*p.p.m.*
Bowie fine sandy loam	7–10	5.4	84	4
Crockett fine sandy loam	7–19	6.0	91	8
Crockett very fine sandy loam	0–7	5.2	84	0
	7–13	4.7	55	31
Edna fine sandy loam	0–7	6.2	74	12
	7–19	6.1	70	12
Garner clay	0–7	5.4	86	48
	14–24	5.3	70	
Hockley fine sandy loam	0–7	6.4	65	1
	7–19	5.8	44	2
Hunt black clay	0–7	6.4	10	0
Kirvin fine sandy loam	7–19	4.4	72	8
Lake Charles clay	7–19	5.0	82	
Leaf fine sandy loam	0–3	5.1	61	5
	3–7	5.5	65	5
	15–19	4.7	65	30
Lufkin fine sandy loam	7–10	5.1	72	16
	7–19	4.9	66	25
Nacogdoches fine sandy loam	0–7	5.4	45	1
	7–19	5.2	63	1
Refugio loamy fine sand	0–7	6.9	34	0
	10–20	5.8	87	13
Ruston fine sandy loam	0–7	5.4	31	1
	7–19	5.2	62	0
Segno fine sandy loam	0–7	5.5	47	0
	7–19	4.6	72	0
Susquehanna fine sandy loam	7–18	5.3	75	6
	18–24	4.8	67	35
Susquehanna very fine sandy loam	0–12	5.9	76	7
Tabor fine sandy loam	0–7	5.1	68	3
	7–18	4.9	56	0
	19–36	4.5	63	21
Wilson clay	7–14	5.7	95	
Wilson clay loam	7–19	6.4	38	0
Wilson fine sandy loam	0–7	6.2	51	
Wilson very fine sandy loam	7–19	6.4	63	0

55 p.p.m. in 4 days, and 63 p.p.m. in 8 days. In about two-thirds of the tests lasting 2 days, from 15 to 44 p.p.m. of nitrate nitrogen was produced, probably by the decomposition of nitrous acid into NO and nitric acid as claimed by Turtschin, as 2 days was too short for appreciable nitrification to occur. Similar production of nitrates was obtained in the experiments made for 4 and for 8 days. The loss of nitrogen with some soils also appears to increase with length of the incubation period. The losses, however, are not proportional to the degree of acidity as indicated by the pH value of the soils. The net losses of nitrogen for each of the soils reacting 8 days are given in table 1.

When calcium carbonate was added, the average loss of nitrogen was 5 p.p.m. in 2 days, 8 p.p.m. in 4 days, and 9 p.p.m. in 8 days. Six of the soil samples lost over 20 per cent of the nitrite nitrogen in spite of the addition of calcium carbonate. The calcium carbonate added may not have been sufficient to neutralize the acidity or it may not have reacted with the acid soil particles during the short time of contact. This also is in agreement with the results of Turtschin. The results in table 1 show that nitrites may be retained in many soils without loss when they contain sufficient quantities of calcium carbonate.

POSSIBLE LOSSES OF NITRITE NITROGEN DURING NITRIFICATION OF AMMONIUM SULFATE IN ACID SOILS

Since the results of the foregoing experiment confirmed previous evidence that considerable losses of nitrogen may occur when nitrites are added to acid soils, it was thought necessary to ascertain whether losses occur in the nitrification of ammonium sulfate, as well as from sodium nitrite, for when the ammonia is converted to nitrites, these might possibly be decomposed in acid soils with loss of nitrogen. Turtschin (5) considered the decomposition to occur as follows:

$$\text{H-soil} + \text{NaNO}_2 = \text{HNO}_2 + \text{Na-soil}$$

$$3\text{HNO}_2 = 2\text{NO} + \text{HNO}_3 + \text{H}_2\text{O}$$

$$2\text{HNO}_2 = \text{N}_2\text{O}_3 + \text{H}_2\text{O}$$

Turtschin also claimed that the nitrous acid also combined to a small extent with the organic matter of the soil. These organic compounds probably undergo nitrification, with production of nitrates.

When calcium carbonate is added to some acid soils, all the ammonia added can eventually be recovered in the form of nitrates. If calcium carbonate is not first added to such acid soils, the ammonia added may be changed partly to nitrites, which, in turn, may be decomposed and part of the nitrogen lost. If calcium carbonate is added after this loss takes place, the quantities of nitrates then produced will be less than those produced when the calcium carbonate was added at the beginning of the experiment. This experiment would thus indicate whether or not there is a loss of nitrogen in the process of nitrification in acid soils which decompose nitrites chemically.

To test this possibility, 24 samples of acid soils were used. Four cultures were prepared from each soil, all receiving ammonium sulfate and all being inoculated with 10 cc. of a suspension of 20 gm. of actively nitrifying soil in 500 cc. of water, two of the four cultures also receiving an addition of calcium carbonate. All were then incubated at 35°C. After 28 days, each culture was emptied into a porcelain dish, mixed thoroughly with a spatula, and

TABLE 2

Effect of delayed application of calcium carbonate upon nitrification in acid soils

Results in parts nitrogen per million of soil

	DEPTH	N IN SOIL WITHOUT CALCIUM CARBONATE	N IN SOIL WITH CALCIUM CARBONATE ADDED		LOSS OF N
			At beginning	After 28 days	
	inches	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
Crockett very fine sandy loam	0–7	135	493	556	0
	7–13	3	531	173	358
Garner clay	0–7	0	669	377	292
	14–24	0	550	139	411
Hunt black clay	0–7	294	669	631	38
Kirvin fine sandy loam	7–19	0	525	398	127
Lake Charles clay	7–19	0	613	277	336
Leaf fine sandy loam	0–3	135	456	513	0
	3–7	6	284	295	0
	15–19	3	556	199	357
Lufkin fine sandy loam	7–19	3	538	518	20
	7–10	0	488	433	55
Nacogdoches fine sandy loam	7–19	4	563	600	0
Refugio loamy fine sand	10–23	0	563	613	0
Segno fine sandy loam	18–24	0	513	556	0
Susquehanna fine sandy loam	7–18	3	425	538	0
	18–24	2	519	49	470
Tabor fine sandy loam	0–7	138	494	544	0
	7–18	66	481	538	0
	19–36	3	525	77	448
Wilson clay	7–14	0	619	688	0
Wilson clay loam	7–19	88	619	606	13
Wilson fine sandy loam	0–7	17	519	575	0
Wilson very fine sandy loam	7–19	35	544	544	0

calcium carbonate was added to the cultures which had not received calcium carbonate at the beginning of the experiment. All the cultures were returned to their beakers and incubated at 35°C. for 28 more days. Nitrates and nitrites were then determined as usual (1). The results of this work are given in table 2. In 16 of the 24 soil samples, the amount of nitrogen nitrified was virtually the same in the cultures to which the calcium carbonate was added at the beginning of the experiment as in the cultures to which it was

added after 28 days' incubation. There was no loss of nitrogen from these 16 soils. In the other eight soils, however, the amount of nitrogen recovered was much less in the cultures which received the addition of calcium carbonate after 28 days' incubation than in those which received the calcium carbonate at the beginning of the experiment. This indicated either loss of nitrogen or incomplete nitrification in those cultures.

It was thought possible that the low production of nitrates in the eight soils might have been due to the presence, at the end of the 28 days, when the calcium carbonate was added, of insufficient numbers of nitrifying organisms as a result of previous unfavorable conditions for growth. The experiment was accordingly repeated, with a second addition of inoculating liquid to all the cultures at the end of the first 28 days. The results of this experiment are given in table 3. There was no loss of nitrogen from most of the soils. With the excep-

TABLE 3

Effect of second inoculation on apparent loss of nitrogen from soil with delayed application of calcium carbonate

Results in parts nitrogen per million of soil

SOIL TYPE	DEPTH	N IN SOIL WITH $CaCO_3$ ADDED		APPARENT LOSS OF N
		At beginning	After 28 days	
	inches	*p.p.m.*	*p.p.m.*	*p.p.m.*
Crockett very fine sandy loam	7–13	563	619	0
Garner clay	0–7	638	588	50
	14–24	588	500	88
Kirvin fine sandy loam	7–19	538	525	13
Lake Charles clay	7–19	576	535	41
Leaf fine sandy loam	15–19	563	494	69
Susquehanna fine sandy loam	18–24	291	189	102
Tabor fine sandy loam	19–36	526	519	7

tion of Garner clay, these samples are all subsurface soils. The differences found in the previous experiment between most of the soils which received calcium carbonate at the beginning and those which did not, were thus due to an insufficient number of nitrifying organisms at the time of the second addition of calcium carbonate. But there were still differences in the quantities of nitrite and nitrate nitrogen in five of the eight soils, and these differences might be due to loss of nitrite nitrogen. The possible loss of nitrogen from Susquehanna fine sandy loam is 102 p.p.m., which is 20 per cent of the ammonia nitrogen added and over 33 per cent of the nitrite and nitrate nitrogen produced in the culture which received calcium carbonate at the beginning of the experiment. With the 14–24-inch layer of Garner clay, the possible loss is 88 p.p.m., or 17 per cent of the nitrogen added. With Leaf fine sandy loam, the possible loss is 69 p.p.m., or 14 per cent of the nitrogen added as ammonia.

With the surface layer of Garner clay, it is 50 p.p.m., or 10 per cent of the nitrogen added, and with Lake Charles clay, it is 41 p.p.m. or 8.2 per cent of the nitrogen added. These possible losses may, however, be due to the failure of the ammonia completely to nitrify in the cultures to which calcium carbonate was added after 28 days.

Another experiment, similar to the one described, was performed with four of the soils which apparently lost nitrogen. A sufficient supply of the other soil was not available. Ammonia nitrogen, as well as nitric and nitrate nitrogen, was determined. To determine ammonia nitrogen a portion from each culture equivalent to 50 gm. of dry soil was washed with 10 per cent potassium sulfate solution into a Kjeldahl flask. About 1 gm. of magnesium oxide was added with a pinch of zinc, and distillation was carried on with a low flame. The distillate was collected in 10 cc. of 0.2 *N* hydrochloric acid and then titrated with 0.1 *N* ammonium hydroxide. The results are given in table 4

TABLE 4

Effect on loss of nitrogen of calcium carbonate added at the beginning and after 28 days of incubation

	DEPTH	AT THE BEGINNING			AFTER 28 DAYS' INCUBATION			LOSS OF NITROGEN
		Nitric N	Ammonia N	Total N	Nitric N	Ammonia N	Total N	
	inches	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
Garner clay	14–24	550	10	560	531	36	567	0
Lake Charles clay	7–19	575	14	589	481	157	638	0
Leaf fine sandy loam	15–19	550	7	557	575	10	585	0
Susquehanna fine sandy loam	18–24	424	85	509	69	343	412	97

No nitrites were found. There was no loss of nitrogen with three of the soils, but with Susquehanna fine sandy loam (subsurface), there was an apparent deficiency of 97 p.p.m. of nitrogen, nearly 20 per cent of the quantity added. This is larger than the limit of error and indicates a possibility of a loss of nitrogen. These samples were all heavy subsurface soils.

This experiment was again repeated, using subsurface layers of Lake Charles clay and Susquehanna fine sandy loam. Again there was no loss of nitrogen with Lake Charles clay, but some loss of nitrogen occurred with Susquehanna fine sandy loam. Thus it appears that there is no loss of nitrogen during the nitrification of ammonium sulfate in acid soils, except possibly in rare cases. Further investigation as to the occurrence of such soils is needed.

SUMMARY

Previous statements to the effect that nitrites are decomposed by acid soils are confirmed. There was no loss of nitrogen which could be ascribed to forma-

tion and decomposition of nitrites during the nitrification of ammonium sulfate in 23 of 24 soils which require additions of calcium carbonate for good nitrification. There was some loss with one of the subsurface soils, indicating that in rare cases nitrites may be formed during the nitrification of ammonium sulfate and decomposed chemically in acid soils with loss of nitrogen.

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PROPERTIES OF SOILS FROM NORTH AMERICAN ARCTIC REGIONS

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Soils of the far North, though of very minor importance insofar as agriculture is concerned, are of considerable interest as a means of extending our knowledge of the influence of the temperature and other factors which affect soil development on various kinds of parent rock.

The U. S. Department of Agriculture has, for a period of years, given considerable attention to relationships between the obvious characteristics used in the classification of soils and the chemical characteristics of the soils, particularly of their colloidal fractions. The materials collected for the present study, through the facilities of the Catholic University of America, have offered the first opportunity to examine soils, or, more exactly, materials exhibiting effects of incipient soil-forming processes, from arctic regions of northeastern North America.

One of the authors[3], in annual visits to regions as far north as the outposts of human habitation, has collected much material of scientific interest. The Soil Chemistry and Physics Research Division felt that detailed examinations of some of the soil materials collected in these regions would be of considerable value. Such data would assist in the tracing northward of variations in soil characteristics to points beyond those previously considered in detail.

GENERAL CHARACTERISTICS OF ARCTIC SOILS

The influences of mechanical weathering forces, particularly those associated with freezing, thawing, and wind action, rather than those of the typical soil-forming processes of temperate zones, predominate in arctic regions. The sparse vegetation favors the activity of mechanical forces, since much of the surface is exposed except under snow cover. The soils of these regions are characterized by the presence of unweathered rocks and rock fragments, and in this respect they are comparable to the lithosols situated at the highest altitudes of mountains in more temperate regions. The normal soil-forming processes of eluviation and illuviation are greatly retarded under the frigid climatic conditions.

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The term "tundra" is often rather loosely applied to a wide range of highly organic soils of the vast treeless arctic regions and appears to have greater significance geographically or climatically than with reference to very definite soil formations. Nevertheless, certain general characteristics of tundra soils are recognized as being more or less typical (4, 11, 13, 15).

Under such conditions where profile development occurs, tundra soil formation appears to be related to the marsh type resulting from excessive moisture conditions (7, 11, 15); much of the soil surface is overlaid with peat or muck.

The region of North America, designated as tundra, embraces areas north of a line running roughly in a southeasterly direction from northern Alaska to the southern boundaries of Hudson Bay and including the northern and northeastern coastal areas of Labrador, according to a U. S. Department of Agriculture soil distribution map (12). A map prepared by Canadian authorities is in agreement with this general designation.[4]

Expeditions have been made by Russian and other scientists for the purpose of studying general conditions in the arctic. A very limited number of chemical and physical data regarding the arctic or tundra soils, however, is available. The general subject matter has been reviewed by Joffe (11), who notes the almost complete absence of definite information concerning soils of the arctic regions of North America with the exception of that found in the research of Canadian investigators (18, 20). The latter have dealt more specifically with geological formations and vegetation than with soils of the northern provinces of Canada. The work of Meinardus (13) summarizes the more important chemical and physical data of far northern soils which have been published by various authors. These data concern chiefly whole soils and parent rocks. Data for colloids or other soil fractions are apparently lacking.

The phenomenon of the perpetually frozen subsoil of vast areas of northern Asia has been described by Nikiforoff (16). This condition is known to exist also in the arctic regions of North America, although its exact extent is not known.

Arctic conditions frequently give rise to peculiar soil formations, among which are polygon fields. These are characterized by a network of cracks or fissures of remarkably uniform hexagonal or other shapes, as described by different writers (13, 17).

DESCRIPTION OF SAMPLES

The soils examined in this investigation were taken from widely separated areas ranging from a latitude of about 58° north at Churchill, Manitoba, to as far north as Craig Harbour, Ellesmere Island, in a latitude of about 76°. The expeditions beyond Churchill were made by boat, and the collections were necessarily made at points not very far from the seashore. The topography was, for the most part, moderately rough, barren rocks being exposed over

[4] Privately communicated by G. N. Runke, Guelph, Ontario.

much of the area. The climate is extremely rigorous. The season when the temperature is high enough to permit thawing at the surface is very short, and hence the vegetation is sparse. This consists primarily of mosses, lichens, and a few stunted plants chiefly of the botanical families Salicaceae and Ericaceae. Certain species of willows 8 to 16 inches high are not uncommon at these northern outposts of vegetation. Organic residues do not readily decompose but tend, rather, to accumulate on the surface as peat or peatlike materials.

Soil profile development in these arctic regions is so markedly in its infancy that no appreciable differentiation into horizons was observed, at least in the areas of relatively rugged topography near the seashore from which most of the materials were collected. Hard rock was usually found so near the surface that no uniform depth of sampling or method of taking samples was practicable. Surface materials to a depth of 6 inches or less were usually collected for laboratory examination. Several of the samples were taken in small shallow depressions into which organic and inorganic materials had been washed from closely adjacent higher levels.

Thirty-seven samples were examined. The pH was determined by the hydrogen electrode on all the soil materials; mechanical analyses were made on 25, or on all except a few of very high organic matter content. Total ash, nitrogen, and organic carbon were determined on 14 samples of high and widely varying organic matter content. Total or partial analyses, depending upon the size of sample available, were made on the ash from ignition of six of the organic samples. The colloids were extracted from nine of the samples with clay contents of about 4 per cent or greater, and total analyses were made of each.

Brief descriptions of the samples, including geographical location and nature of the parent rocks and vegetation, are presented in table 1. The results of pH determinations, included in this table for the sake of convenience, show that most of the samples were acid and none were strongly alkaline.

The approximate locations of the samples and their distribution are indicated on the geological sketch map (fig. 1).

Photographs shown in plate 1 were taken in the regions where some of the samples were collected.

MECHANICAL COMPOSITION

To a considerable extent the mechanical composition of soil is influenced by climatic conditions. Certain relations have been pointed out between temperature and rainfall and the clay contents of soils (8, 10). High temperature and high rainfall tend toward the formation of clay soils except as eluviation processes remove the clay fractions from certain parts of the profiles to deposit this material in others. The low annual temperature together with moderate rainfall in most parts of the northern regions covered would be expected to result in very limited clay formation. This fact is brought out by the mechanical analyses of the samples as a whole, shown in table 2.

TABLE 1

Location and description of samples

SAMPLE NUMBER	LOCATION, LATITUDE, AND LONGITUDE	ELEVATION OR ALTITUDE	GENERAL DESCRIPTION*		GEOLOGICAL CLASSIFICATION AND PARENT ROCKS	VEGETATION	pH
			Material greater than 2 mm.	Material less than 2 mm.			
		feet					
C3471	Churchill, Man., 58° 40′ N., 94° 15′ W.	100–150	(97%) Heterogeneous mixture of stream pebbles of granite, schists, and limestone (50%)	(3%) Inorganic fragments mixed with dark brown organic material. Good drainage	Silurian and Cambro-Silurian-Archaean; Athabasca sandstone	Hedysarum, Vaccinium, mosses, lichens	6.7
C3472	Churchill, Man., 58° 40′ N., 94° 15′ W.	100–150	Nearly pure quartz fragments and sand	Small amount of black organic matter, origin probably from lichens. No drainage	Silurian and Cambro-Silurian-Archaean; West Fort formation	Potentilla, Pyrola, lichens, Hedysarum; a few Salicaceae and Betulaceae	5.6
C3474	Chesterfield Inlet, N.W.T., 63° 25′ N., 90° 40′ W.	125–150	(98%) About ¾ mica schist, ¼ granite, 40% each of biotite and orthoclase, 20% quartz	(2%) Black organic matter a few inches deep, overlying granite. No drainage	Archaean	Ericacea, Betulaceae. No Leguminosae	5.5
C3475**	Wolstenholme, Que., 62° N., 77° W.	900–1,000	(36%) Well-weathered fragments of biotite and granite, rusty from decomposition. Order of attack probably feldspar, then biotite	(64%) Brown, light, friable material of sandy texture overlying granite. No drainage	Precambrian, unclassified (sediments, volcanics and intrusives)	Empetrum, Vaccinium, Arctostaphylos. No Leguminosae	4.2
C3476	Dorset, Baffin Island, N.W.T., 64° N., 76° W.	500–600	(36%) Almost entirely pink granite	(64%) Grayish friable sand. On a plateau. Poor or no drainage	Archaean and Precambrian (supposed) granite, gneiss	Oxytropis, Silene, Stellaria	4.7
C3478	Southampton Island, N.W.T., 63° N., 82° W.	100–150	(84%) Disintegrated pink and gray granite (50%), mixed with equal amount of fine-grained limestone, shell, and plant remains	(16%) Brown or dark brown organic fragments mixed with high proportion of sand. In an Arctic garden one year, virtually sterile	Silurian and Cambro-Silurian (west and south), Archaean (north and east)	Lichens, Saxifragaceae, Crucifereae	7.1
C3479	Wolstenholme, Que., 62° N., 77° W.	1,500	None	Brown, finely fibrous peat, with no mineral admixture, overlying granite. Surrounding rock devoid of soil	Precambrian, unclassified (sediments, volcanics and intrusives)	Grassy meadow; Poa, Alopecurus	4.2
C3480	Lake Harbour, N.W.T., 62° N., 70° W.	400–500	(16%) Angular pieces of quartz, about 85% silica, 10% feldspar, 5% mica, small amount buff sand. Covered with moss	(84%) Dark brown lumpy peaty material containing fine rootlets and sandy constituents	Archaean or Precambrian (supposed) granite, gneiss	Mixed heath, Carex, Oxytropis or Astragalus, mosses	5.7

C3481	Lake Harbour, N.W.T., 62° N., 70° W.	750	(36%) Decomposed buff granite, 50% feldspar, 25% quartz, little biotite mica. One piece of plagioclase feldspar	(64%) Similar in appearance to C3480 but contains a higher proportion of sandy constituents	Archaean or Precambrian (supposed) granite, gneiss	Astragalus, Pyrola, Saxifragaceae	5.2
C3482	Lake Harbour, N.W.T., 62° N., 70° W.	400	(41%) Disintegrated pink granite. Quartz 75%, feldspar 20%, hornblende 5%, slightly decomposed	(59%) Brown, sandy material containing little organic matter with particles of lichens	Archaean or Precambrian (supposed) granite, gneiss	Lichens, Ericaceae	5.4
C3483	Lake Harbour, N.W.T., 62° N., 70° W.	600	(30%) Weathered fragments of a biotite mica granite. Rusty color. Quartz 50%, orthoclase 40%, biotite 10%	(70%) Brown or dark brown sand. Material overlying granite	Archaean or Precambrian (supposed) granite, gneiss	Lichens, Crucifereae	5.1
C3484	Pond's Inlet, N.W.T., 72° 50′ N., 76° 40′ W. Plateau at foot of an elevation 1000 feet	200–300	(61%) Angular pebbles of assorted crystallines as schists, quartzites, and pink and red granites. One small piece of limestone (1%)	(39%) Gray sandy material, friable. Good drainage. Subsoil probably stream deposits	Precambrian (supposed) granite, gneiss, tertiary and coal deposits	Very sparse; lichens and dead Salix	6.8
C3485	Craig Harbour, Ellesmere Island, N.W.T., 76° 20′ N., 81° 30′ W. At foot of a receding glacier	75–100	(12%) Pink hornblende talus with about 10% of marble ($CaCO_3$) breccia	(88%) Gray sand. Good drainage. Subsoil of glacial deposit	Archaean or Precambrian (supposed) granite	Saxifragaceae and other seed plants	7.6
C3486	Craig Harbour, Ellesmere Island, N.W.T., 76° 20′ N., 81° 30′ W.	1,500	(55%) Essentially a quartz-feldspar aggregate. No limestone. Granite scrap 60%, gneiss 20%	(45%) Light gray sandy material. Underlying stratum of granitic material. Good drainage	Archaean or Precambrian (supposed) granite	Sparse; Cardamine, Draba, Saxifragaceae, and a few papaver	6.3
C3487	Dundas, North Devon Island, N.W.T., 82° W. West of H.B.C. post	100	(21%) Quartz 50%, orthoclase 30%, hornblende 10%, garnet 10%. No mica. Decomposition only superficial	(79%) Gray sandy material with low content of organic matter and clay. No drainage	Archaean or Precambrian granite, gneiss (east), Lower Paleozoic (west)	Ericaceae, sedges, and grasses	5.1
C3488	Dundas, North Devon Island, N.W.T., 82° W. Southeast of H.B.C. post	450	(24%) Ferro-magnesian minerals (biotite and hornblende)	(76%) Gray, sandy, friable material with small contents of organic matter overlying granite. No drainage	Archaean or Precambrian granite, gneiss (east), Lower Paleozoic (west)	Empetraceae, grasses, and sedges	5.7
C3489	Arctic Bay, Baffin Island, N.W.T., 73° N., 74° W. Southwest of H.B.C.	750	(39%) Weathered limestone. A few aggregates of well-crystallized quartz. Red color	(61%) Red sandy loam. Subsoil is a colluvial debris. Poor drainage	Silurian and Cambro-Silurian-Lower Paleozoic (noncoal bearing)	Vaccinium, Empetraceae, grasses, sedges	8.3
C3490	Arctic Bay, Baffin Island, N.W.T. 73° N., 74° W. On shallow depression in a large bare rock	200	(95%) About 75% tabular hydromica schist, with 15% quartzite and 10% granite scrap. No limestone.	(5%) Gray, dried organic material overlying powdery granite. No drainage	Silurian and Cambro-Silurian-Lower Paleozoic (noncoal bearing)	No seed plants. Lichens	5.4

* Numbers in parentheses in each column represent percentages of total material fractionated by the 2-mm. mesh sieve.

TABLE 1—*Concluded*

SAMPLE NUMBER	LOCATION, LATITUDE, AND LONGITUDE	ELEVATION OR ALTITUDE	GENERAL DESCRIPTION*		GEOLOGICAL CLASSIFICATION AND PARENT ROCKS	VEGETATION	pH
			Material greater than 2 mm.	Material less than 2 mm.			
		feet					
C3491	Arctic Bay, Baffin Island, N.W.T., 73° N., 74° W. Southeast of H.B.C. post; a mountain peak, 1800 feet altitude	300	None	Dark brown, finely fibrous peat, covered by a layer of dried moss. Considerable mineral material present. Deposit as much as 6 to 8 feet deep, resting on sandstone	Silurian and Cambro-Silurian-Lower Paleozoic (noncoal bearing)	Vaccinium, Empetrum	6.0
C3492	Clyde River, N.W.T., 70° N., 68° W. Northwest of H.B.C. post. On large isolated rock	100	(40%) Weathered, but still angular, fragments of biotite granite. No limestone	(60%) Grayish organic matter overlying granite. No drainage	Archaean and Precambrian (supposed) granite	Lichens, mosses, Tofieldia	5.3
C3493	Port Burwell, N.W.T., 60° N., 64° W.	50–100	None	Brown, finely fibrous peat, very little mineral admixture evident. Damp slope	Precambrian, unclassified (chiefly granite and granite-gneiss), Silurian (?)	Heavy vegetation; Ericaceae, grasses, sedges and mosses	5.8
C3494	Port Burwell, N.W.T., 60° N., 64° W. Southwest of H.B.C. post	100–150	(11%) Angular weathered gray biotite granite. Superficially pan-dried with sandy material. 50% feldspar, 30% quartz	(89%) Dark gray sandy loam, 6 to 8 inches deep, underlying stratum high in organic matter, resting on granite. Poor drainage		Sparse grasses, Vaccinium, Ericaceae	4.9
C3495	Port Burwell, N.W.T., 60° N., 64° W.	300	(7%) Slightly rounded pebbles, with powdered and sandy material; 10% limestone, 5% hematite	(93%) Polygonic sandy loam, orientated northwest. Thin layer of organic matter at 3-inch depth. Poor drainage		Naked surface but surrounded by Dryas, Vaccinium	7.6
C3496	Port Burwell, N.W.T., 60° N., 64° W. Near old Moravian mission	150–200	(11%) Crystalline metamorphics with a little sandy material. No organic matter. 75% pink granite, 10% blue granite	(89%) Dark brown clayey material overlying gneiss. No drainage		Lichens, Ericaceae	5.7
C3497	Port Burwell, N.W.T., 60° N., 64° W. At the foot of late snows	125–150	None	Brown sandy loam. Poor drainage		Sparse; Saxifragaceae, Draba	5.7
C3498	Dundas, North Devon Island, N.W.T., 74° N., 82° W.	400	None	Brown, lumpy peat or muck, with plant remains, fairly well decomposed. Some fine sand. Poor drainage	Archaean or Precambrian granite, gneiss (east), Lower Paleozoic (west)	Empetraceae, sedges, grasses	5.7

C3500	Wakeham Bay, Que., 62° N., 70° W.	500–600	(11%) Hornblende-biotite, schist with some quartzite and vein quartz; 25% feldspar, 15% hornblende, 10% biotite	(89%) Brown loamy sand material. Poor drainage	Precambrian, unclassified (sediments, volcanics, and intrusives), Archaean	Ericaceae, Cruciferae	4.9
C3502	Repulse Bay, N.W.T., 66° N., 86° W.	600	None	Dark brown loamy sand material. Poor drainage	Archaean gneiss, dykes of quarts, pegmatites, diabase	Lichens, mosses	4.6
C3503	Churchill, Man., 58° 40′ N., 94° 15′ W.	100–150	None	Light brown sphagnum and polytrichum moss peat, well preserved. No mineral admixture. Good drainage	Silurian and Cambro-Silurian-Archaean	None	3.8
C3504	Churchill, Man., 58° 40′ N., 94° 15′ W.	100–150	None	Light brown sphagnum moss peat, well preserved. No mineral admixture. Good drainage	Silurian and Cambro-Silurian-Archaean, West Fort	None	4.1
C3505	Churchill, Man., 58° 40′ N., 94° 15′ W.	100–150	None	Light brown to dark brown fibrous peat containing woody fragments and sphagnum moss, well preserved. Poor drainage	Silurian and Cambro-Silurian-Archaean, West Fort	Salicaceae	6.7
C3506	Churchill, Man., 58° 40′ N., 94° 15′ W.	100–150	(23%) Fossiliferous limestone, some of which is slightly sandy (quartzite); 90% $CaCO_3$, 10% SiO_2	(77%) Dark brown fairly well decomposed, granular organic material. Admixture of light straw-colored fragments and sandy material	Silurian and Cambro-Silurian-Archaean, West Fort	Epilobium, Hedysarum	6.5
C3507	Churchill, Man., 58° 40′ N., 94° 15′ W.	100–150	(1%) Pyritiferous gray quartzite with a little admixture of pink granite; 90% SiO_2	(99%) Brown coarse sandy material. Poor drainage	Silurian and Cambro-Silurian-Archaean, West Fort	Salicaceae, Astragalus	7.3
C3508	Churchill, Man., 58° 40′ N., 94° 15′ W.	100–150	(21%) About ½ twig-like woody material. Mineral matter containing about 60% limestone and 5% pyrolusite	(79%) Dark brown organic material with a considerable quantity of light, straw-colored undecomposed fragments	Silurian and Cambro-Silurian-Archaean, West Fort	Ericaceae	6.7
C3519	Letty Harbour, N.W.T., 69° N., 124° W.	200–300	(27%) Calcareous pebble bed; 70% limestone, 15% mica schist, 10% pink granite, 5% quartzite. All particles covered with $CaCO_3$ dust	(73%) Light brown clay loam with little or no organic matter. Good drainage. Frozen subsoil	Paleozoic	Oxytropis	8.0
C3519A	Letty Harbour, N.W.T., 69° N., 124° W.	200–300	(6%) Calcareous rounded pebbles covered with $CaCO_3$ dust 50%; quartz 20%; stony fragments	(94%) Brown silt loam. Subsoil frozen. Good drainage	Paleozoic	Oxytropis	8.0
C4354	Chateau Bay, Labrador		Lichen vegetation				

An outstanding feature of the data is the large amount of material falling in the larger size groups, such as gravel and coarse sand. Only three of the soils had as much as approximately 20 per cent clay, and nearly half of the soils had less than 5 per cent. In many cases, large quantities of the sample taken consisted of material greater than 2 mm. in diameter which was examined only to the extent noted in the descriptions of table 1.

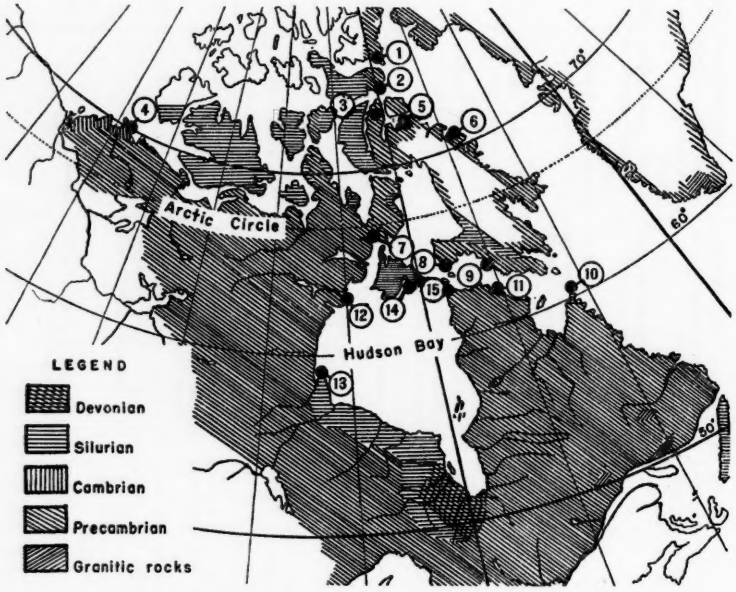

FIG. 1. SKETCH MAP OF NORTHEASTERN NORTH AMERICA, INDICATING GEOGRAPHICAL LOCATIONS OF THE SAMPLES COLLECTED

Key relating encircled numbers on map to laboratory numbers: 1, C3485-86; 2, C3487-88, C3498; 3, C3489-91; 4, C3519-19A; 5, C3484; 6, C3492; 7, C3502; 8, C3476; 9, C3480-83; 10, C3493-97; 11, C3500; 12, C3474; 13, C3471-72, C3503-08; 14, C3478; 15, C3475, C3479.

ORGANIC MATERIALS

Low-growing vegetation such as lichens, mosses, sedges, and heath shrubs, which have already been mentioned, are characteristic of the arctic under conditions where it is at all possible for them to become established. The growing season is extremely short, and consequently only a small annual addition is made to the supply of organic matter in the soil. The microbiological activity, however, is greatly reduced by the prevailing low temperatures, and the plant remains tend, therefore, to be readily preserved in the form of peat or in other forms of organic matter.

In some cases the organic materials had accumulated in small depressions

in the rocks, and in other cases vegetation had formed peat essentially in place. An admixture of considerable sand with the organic matter was frequently observed.

All of the samples having a high content of organic matter were analyzed for ash, carbon, and nitrogen with the object of obtaining characterizing data, particularly carbon-nitrogen ratios. These results are shown in table 3.

TABLE 2

*Mechanical analyses of soils from northeastern North America**

LABORATORY NUMBER	FIELD NUMBER	FINE GRAVEL 2–1 MM.	COARSE SAND 1–0.5 MM.	MEDIUM SAND 0.5–0.25 MM.	FINE SAND 0.25–0.1 MM.	VERY FINE SAND 0.1–0.05 MM.	SILT 0.05–0.002 MM.	CLAY <0.002 MM.	ORGANIC MATTER BY H_2O_2	MINERAL MATTER DISSOLVED BY H_2O_2
		per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
C3471	I	15.3	18.1	4.7	2.4	1.7	18.7	6.6	31.0	1.5
C3472	II	3.6	46.7	5.7	3.2	1.4	12.4	20.1	6.5	0.4
C3474	IV	22.5	34.9	10.6	13.0	4.0	4.2	2.3	7.7	0.8
C3475	V	21.3	25.7	15.1	20.4	5.5	7.8	1.9	2.0	0.3
C3476	VI	32.2	26.5	16.8	14.8	2.9	2.8	1.6	2.2	0.2
C3479	XI	13.2	39.9	14.6	11.3	3.1	4.6	2.2	10.5	0.6
C3482	XII	38.2	30.6	10.1	10.6	2.3	2.2	1.6	4.2	0.2
C3483	XIII	20.7	36.1	18.2	16.1	2.3	2.5	2.3	1.6	0.2
C3484	XIV	18.9	32.5	17.0	18.4	7.2	3.7	1.1	1.1	0.1
C3485	XV	7.5	23.1	17.4	29.4	12.6	6.8	2.2	0.7	0.3
C3486	XVI	28.1	24.0	11.5	16.6	9.0	5.6	1.1	3.6	0.5
C3487	XVII	9.8	12.3	7.4	19.7	17.6	28.3	1.1	3.5	0.3
C3488	XVIII	13.0	18.2	14.3	26.0	13.6	10.5	1.3	2.8	0.3
C3489	XIX	6.1	4.4	3.6	18.4	24.5	38.1	4.1	0.7	0.1
C3490	XX	5.5	7.8	4.4	9.8	8.4	36.8	19.4	7.4	0.5
C3492	XXII	25.8	26.1	11.8	14.9	6.0	6.9	3.9	4.3	0.3
C3494	XXIV	5.2	10.2	7.6	16.7	12.2	28.1	11.4	8.1	0.5
C3495	XXV	6.6	10.9	8.6	18.5	13.7	24.0	15.9	1.5	0.3
C3496	XXVI	12.6	13.8	8.2	16.6	15.0	28.4	3.7	1.5	0.2
C3497	XXVII	2.1	3.2	4.9	23.5	24.1	27.7	8.7	5.4	0.4
C3500	XL	7.8	14.4	16.8	28.5	17.2	11.2	1.6	2.3	0.2
C3502	XLI	24.1	25.9	9.7	10.0	2.4	11.4	3.5	12.4	0.6
C3507	330828-13	2.1	75.2	8.6	1.3	0.7	6.8	2.4	2.6	0.3
C3519	340816-26	2.4	2.3	2.1	7.3	11.8	45.5	27.1	1.1	0.4
C3519A	340816-25	2.1	2.4	2.5	7.4	18.2	56.7	7.9	2.4	0.4

* Mechanical analyses by T. M. Shaw and E. F. Miles.

A very wide range of carbon-nitrogen ratios is evident. This is not unusual, however, as variations of similar magnitude have been observed in analyses of peats or mucks collected in the United States (5, 6). In fact, the carbon-nitrogen ratios shown in table 3 are not greatly different from those of the American peats and mucks just referred to. The sample of sphagnum moss peat (No. C3504), for example, has the high ratio of 84.0, which is of the same order of magnitude as that corresponding to the same variety of peat collected

from various deposits of Maine (5). A number of the samples have carbon-nitrogen ratios around 16 to 18, which are characteristic of mucks and not greatly different from those of the organic matter of many soils in temperate climates (2). The carbon contents appear to be somewhat low when calculations are made on an ash-free basis, at least in the samples where the ash content was sufficiently low to justify confidence in the reliability of such calculations. The sphagnum moss peat samples have carbon contents of 45 and 46 per cent on the ash-free basis, whereas the Maine sphagnum peats previously analyzed had carbon contents of 50 per cent or higher. Carbon contents of other arctic peat samples ranged from 51 to 55 per cent, whereas percentages

TABLE 3

Partial analyses of peats or organic materials from northeastern North America

SAMPLE NUMBER	AIR-DRY MOISTURE	ASH CONTENT	NITROGEN*	CARBON*		CARBON / NITROGEN RATIO
				Entire sample	Calculated on the ash-free basis†	
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	
C3471	5.81	58.03	1.32	24.14	.....	21.3
C3478	2.42	81.63	0.54	8.75	.....	18.9
C3479	9.25	26.21	2.79	38.82	52.61	16.2
C3480	8.25	50.78	1.67	26.80	.....	18.7
C3481	3.56	70.44	1.03	16.25	.....	18.4
C3491	6.10	63.53	1.28	20.31	.....	18.5
C3493	9.90	35.85	2.40	34.26	53.41	16.7
C3498	7.53	57.69	1.38	21.91	.....	18.5
C3503	9.83	4.89	0.98	43.95	46.21	52.3
C3504	9.27	3.20	0.61	43.96	45.41	84.0
C3505	9.17	37.30	1.52	32.34	51.58	24.8
C3506	6.46	58.88	1.31	21.52	.....	19.2
C3508	5.31	60.84	1.11	20.61	.....	21.7
C4354	9.34	3.17	1.85	34.70	35.83	21.9

* Determinations by J. H. Shimp and A. Yelmgren.

† Calculations were made only on samples containing less than 40 per cent ash.

of 55 to 60 were found to be common in peats in the United States referred to above.

The lichen sample (No. C4354) had an unusually low content of carbon, 34.70 per cent, as compared with that commonly found in fresh plant material. The average carbon content of a considerable variety of vegetation is approximately 45 per cent according to published data (19). Curiously, the nitrogen content of the lichens is relatively high, which accounts for the relatively low carbon-nitrogen ratio of 21.9. The latter value, however, is within the range of carbon-nitrogen ratios of 16 to 200 reported for fresh vegetation (9).

Since lichens are common in the arctic region, they have undoubtedly con-

tributed considerably to the various organic accumulations. Low carbon contents and low carbon-nitrogen ratios may, therefore, be expected in many cases.

ASH COMPOSITION

The ashes of the organic materials which had no significant admixture of extraneous mineral constituents and which were available in sufficient quantity were analyzed in detail as shown in table 4.

Only three of the samples selected for ash analyses (Nos. C3493, C3504, and C3505) can be considered as being peats. The others are perhaps more correctly termed mucks or peaty mucks, as indicated by their physical character and by the magnitude of the ash content.

It is of interest to compare the composition of the ash of the sphagnum peat (No. C3504) with that of the same variety of peat from Maine deposits pre-

TABLE 4

Chemical composition of the ash of peat or highly organic materials from northeastern North America*

SAMPLE NUMBER	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3	IGNITION LOSS	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
C3491	39.96	0.43	11.11	4.10	0.14	15.30	9.66	1.79	0.98	0.59	0.63	15.57	100.26
C3493	55.93	0.40	14.88	12.81	0.40	6.38	2.97	1.79	1.71	0.91	1.72	0.74	100.64
C3498	52.89	0.48	17.34	12.95	0.22	7.22	1.77	2.79	2.23	0.64	0.64	1.69	100.86
C3504	65.53	0.16	8.58	1.84	0.08	10.69	1.78	1.87	1.71	0.43	1.70	6.54	100.91
C3505	71.94	0.60	11.94	3.14	0.05	2.78	1.68	3.23	0.08	0.92	2.14	1.68	100.18
C4354	35.37	0.73	19.19	8.99	0.22	3.41	5.22	13.43	2.46	9.74	Trace	0.84	99.60

* Chemical analyses by G. J. Hough.

viously published (5). The arctic sample of sphagnum peat is markedly higher in silica and potash but lower in sesquioxides, magnesium, and manganese, and much lower in phosphorus and sulfur. Other constituents, including calcium, are more or less similar. Taken as a whole, however, no striking differences were noted in the arctic samples as compared with samples from temperate regions. The contents of sulfur trioxide appear to be distinctly lower in the arctic samples, but insufficient data are at hand to warrant definite conclusions. The content of alumina is considerably greater than that of iron oxide, as has been similarly noted for peats of the United States (5).

The ash of the lichen is notably high in potash and phosphoric acid and is comparatively rich also in alumina, although to a less marked degree. The actual plant tissue, however, cannot be considered as rich in these constituents, since the total ash content was found to be only 3.17 per cent (see table 3).

In the process of ashing, considerable carbonates were formed. The tem-

perature used (about 550°C.) was not adequate actively to decompose these compounds. Hence the ashes show considerable and varying weight losses on ignition.

CHARACTER OF SOIL COLLOIDS

Certain features of the chemical composition of soil colloids give important indications regarding the dominant soil-making processes which have been operative, particularly when profile samples are considered. No data for soils or soil materials from temperate regions are available which closely approximate those here considered from northern latitudes. Samples from azonal soils of the lithosol group which are being developed on mountains essentially above the timber line would be expected to show some resemblance to those of the rough arctic areas. Chemical data for colloids of such soils in the United States are lacking, however. Comparisons with soil colloids of temperate regions, shown in table 5, are given only for the purpose of bringing out broad similarities and differences between the arctic materials and those of soils representative of groups that are well known. Data in various publications dealing with soils of the United States show, with important exceptions, that soils from regions of low rainfall, including the chernozems, tend to have colloids with ratios of silica to total bases ranging from about 5 to 8 (accompanying silica-alumina ratios are 4 or greater); the prairies about 8 to 10; the gray-brown podzolic group somewhat higher; and the red and yellow soils about 18 to 40. The silica-alumina ratios tend to vary inversely with those of silica to total bases. The very low ratios of silica to total bases of the arctic soil colloids together with values of intermediate magnitude for the silica-alumina ratios are indicative of only slight chemical alteration.

Two of the samples included in table 5, Nos. C3489 and C3495, are of particular interest.

Sample C3489 is a soil of distinctly red tint. This material is presumably the residuum from the decomposition and solution of limestone. No doubt the colloid obtained its distinctive characteristics in a former geological age, before the limestones were formed. For this reason the character of the colloid, indicated in part by its relatively low silica-sesquioxide ratio (1.92) does not necessarily reflect current arctic rock-weathering or soil-forming processes.

Sample C3495 is representative of the so-called polygonic soil areas frequently encountered in far northern regions on comparatively shallow clayey alluvial deposits. These are of striking appearance, as pointed out earlier in the text. The process of polygon formation is presumably directly related to a flooding or saturation of the soil with water followed by evaporation and a resultant contraction of the material. Freezing probably also exerts some influence. Table 5 presents the chemical composition of the colloidal fraction of a soil of this kind. The silica-alumina ratio is high but not quite so high as in one of the other samples. A factor of particular importance relative to the shrinkage behavior of this soil would seem to be the ratio silica to total bases,

TABLE 5

*Chemical analyses of the colloids of soils from northeastern North America**

SAMPLE NUMBER	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3	IGNITION LOSS	TOTAL	$\frac{SiO_2}{R_2O_3}$	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{\text{TOTAL BASES}}$
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*			
C3472	42.81	0.75	19.63	7.94	0.04	0.96	3.31	3.16	0.70	0.33	0.38	19.72	99.73	2.94	3.71	4.92
C3489	35.81	0.50	19.91	18.41	0.10	1.62	4.12	3.13	0.17	0.21	0.42	14.93	99.33	1.92	3.05	3.56
C3490	43.46	0.72	23.19	7.89	0.18	0.67	2.74	4.71	0.14	0.27	0.47	15.97	100.41	2.61	3.18	5.45
C3492	26.91	0.69	13.61	8.67	0.02	0.77	2.04	2.01	0.65	0.10	0.74	40.78	96.99†	2.34	3.35	4.64
C3494	31.77	0.76	15.96	12.33	0.19	0.96	3.17	2.29	0.44	0.56	0.58	31.02	100.03	2.26	3.38	4.14
C3495	42.70	0.84	20.26	11.76	0.18	1.88	4.64	3.46	1.03	0.28	0.22	13.44	100.69	2.62	3.58	3.51
C3497	30.55	0.77	15.79	12.30	0.04	0.94	2.81	1.93	0.44	0.56	0.82	32.56	99.51	2.18	3.28	4.44
C3519	45.52	0.60	23.69	9.30	0.09	1.15	4.17	4.57	0.29	0.13	0.11	10.34	99.96	2.61	3.26	4.26
C3519A	38.20	0.60	20.54	12.71	0.06	0.82	2.80	2.73	0.19	0.28	0.43	20.76	100.12	2.27	3.15	5.45
Colloids from three soils of the United States cited for comparison‡																
Pima soil (3)	51.58	0.53	20.24	7.78	0.12	3.39	4.29	2.32	0.07	0.26	0.07	9.39	99.99	3.47	4.32	5.2
Shelby soil (14)	47.49	0.67	24.41	9.99	0.06	1.28	1.98	1.12	0.20	0.12	0.09	13.24	100.65	2.62	3.30	9.1
Davidson soil (1)	36.92	0.92	31.67	16.03	0.06	0.56	0.41	0.37	None	0.18	0.12	13.14	100.38	1.49	1.98	25.4

* Determinations by G. Edgington.

† Contains some copper and perhaps other bases not included in the analysis.

‡ From various publications of the U. S. Department of Agriculture.

which is the lowest found in the group. Perhaps of even greater importance is the sodium content (1.03 per cent Na_2O), which is the highest found in the group; in fact, much higher than is ordinarily found in nonsaline soils. It is well known that the presence of exchangeable sodium in soil colloids tends to increase their capacity for swelling and shrinkage. The high sodium content associated with a pH value as low as 7.6 excludes a possibility of the presence of more than traces of sodium carbonate. A test of the whole soil showed the presence of only about 0.04 per cent of total soluble salts, confirming their nonsaline character.

In view of the rather unusual chemical relations found in most of these colloids it seemed possible that they might differ somewhat crystallographically from those of the large number of colloids from temperate and tropical regions thus far examined. It seemed possible that slightly altered primary minerals might play a greater part. In the United States, soils the deep horizons of which are only moderately weathered, such as in those of the Miami series,

TABLE 6

Mineralogical composition of colloids shown by x-ray examinations and differential thermal analyses

SAMPLE NUMBER	HYDROUS MICA	KAOLINITE	GOETHITE AND HEMATITE
	per cent	*per cent*	*per cent*
C3489	80	10	10
C3490	95	5	..
C3494	90	10	..
C3495	95	5	..
C3519	75	25	..
C3519A	80	20	..

show in their colloids the presence of clay minerals instead of fragments of such primary minerals as feldspars. In order to obtain evidence concerning the fate of primary minerals in soil colloid formation in the far northern latitudes, S. B. Hendricks, of the division of fertilizer research, Bureau of Chemistry and Soils, made x-ray examinations of six samples. His statement follows:

> The separated colloids were examined by differential thermal analysis, and X-ray diffraction patterns were made from oriented and unoriented samples. The presence of organic matter seriously interfered with the heating curves and further caused trouble in obtaining oriented samples for X-ray work. For this reason and because oxides of iron were not removed before identification of the silicate minerals, the results given below [table 6] are not very accurate.[5] The chief constituent in the various samples was hydrous mica, a mineral that is known by many names including illite and ordovician bentonite, intermixed with a minor amount of a kaolin mineral, probably kaolinite.

It is evident that minerals such as feldspars and hornblende, which are presumably present in the coarser granitic material, are not found in determinable

[5] Quantities of samples available were inadequate for the conventional pretreatments.

quantities in the colloid even though these colloids in many ways show but little decomposition. The hydrous mica which predominates is a normal constituent of many soil colloids in considerable quantities.

The samples of soils, or in some cases more strictly soil materials, investigated in this report were collected from regions where typical tundra profiles might have been expected to be found. No evidence of well-defined profile characteristics was observed, however, in the limited areas examined. Since chemical analyses of the colloids of the typical tundra soils are not at hand, no comparison can be made of these with the present data. Such a comparison would furnish additional information relative to the influence of arctic conditions on soil formation. The samples may perhaps be logically classified for the most part as lithosol associates of what is recognized as true tundra. The general chemical character of the surface organic matter would be expected to be similar in both groups. The character of the parent rock, whether rugged and hard or comparatively soft and readily powdered, apparently plays an important role in determining the extent of profile development.

SUMMARY

A group of 37 soils and soil materials collected from the arctic region of northeastern North America were examined by the usual methods. The samples comprised both inorganic and predominately organic materials. Lack of profile development as well as certain chemical and physical characteristics is indicative of their extreme immaturity as soils.

Mechanical analyses of the samples examined showed that a large part of the materials consisted of particles in the coarser size groups. The clay content was generally small, only three of the samples having as much as approximately 20 per cent and a majority of the remainder having less than 5 per cent.

The wide range of carbon-nitrogen ratios in the organic materials was comparable to the variation found in peats and mucks of the United States. The carbon contents, calculated on an ash-free basis, however, appear to be somewhat lower than those of peat samples of this country.

Ash analyses indicated, on the whole, no striking differences, except perhaps for low contents of sulfur, as compared with ashes of peats and mucks from temperate regions.

Examinations of the colloids extracted from a group of the mineral soils show silica-base ratios of 5.5 or lower and accompanying silica-alumina ratios of 3.0 to 3.7. These and other factors are indicative of their extreme immaturity or of only a slight chemical alteration. Hydrous mica was shown by x-ray and heating curves to be the dominant clay mineral present.

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PLATE 1

SEVERAL LOCALITIES FROM WHICH SAMPLES WERE TAKEN FOR EXAMINATION

FIG. 1. Near Churchill, Man., location of sample C3472, showing lichens on rounded rocks and flowers blooming in the depression.

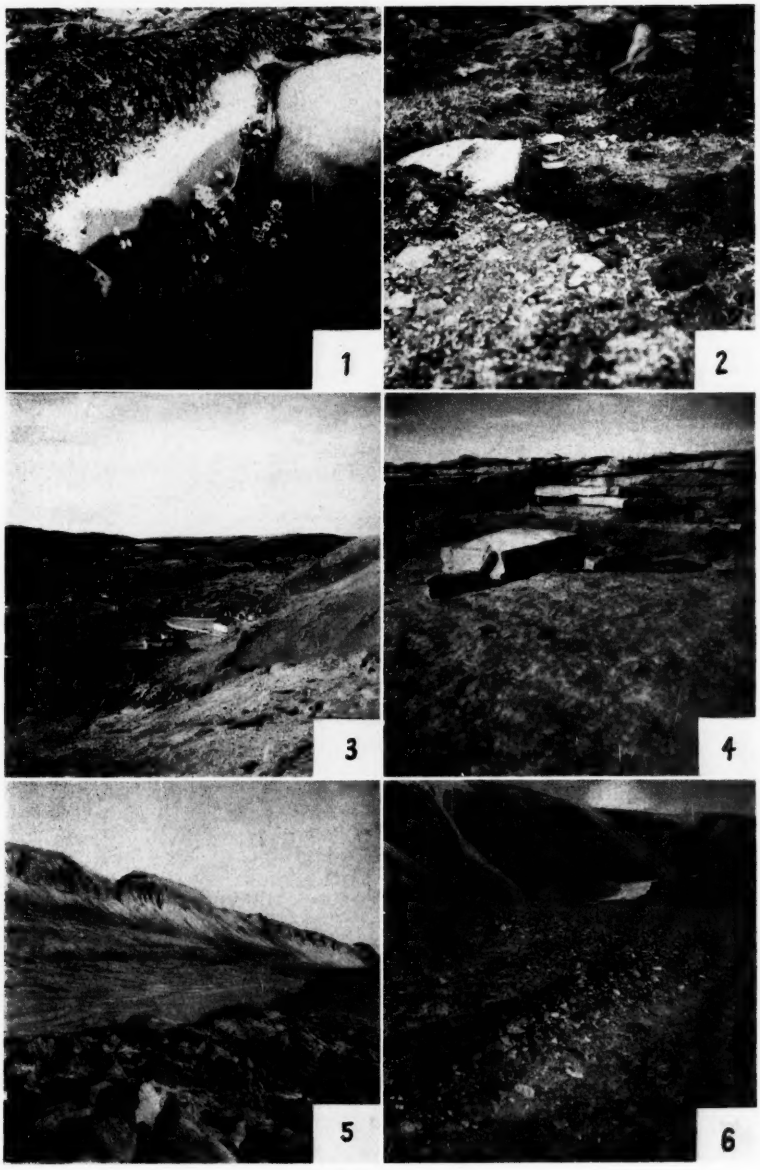
FIG. 2. Port Burwell, N.W.T., location of sample C3494. Sparse covering of grass.

FIG. 3. Lake Harbour, Baffin Island, N.W.T., near a Hudson Bay Company Post, location of samples C3480-83. Some heath vegetation is growing on mountain side in foreground.

FIG. 4. Fairway Island, N.W.T. Some vegetation can be seen near the background.

FIG. 5. Arctic Bay, Baffin Island, N.W.T. Sample C3490 was taken at the line of contact between rocks in foreground and ridge in background.

FIG. 6. Craig Harbour, Ellesmere Island, N.W.T., location of sample C3485. A receding glacier can be seen in the background.



FIGS. 1–6

THE COLLOIDAL CONSTITUENTS OF CALIFORNIA SOILS

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The importance of soil colloids is widely recognized. The permeability of soils to air and water, their adaptability to specific crops, their fertility, their absorptive power, and their tilth are all influenced to a marked degree by the colloidal constituents. For these reasons many soil scientists are actively engaged in research on soil colloids. Perhaps the most elementary questions that can be raised about soil colloids are these: (a) Of what specific substances are soil colloids composed, and (b) are the properties of soils due to the specific kinds of substances of which the colloids are composed, to the amount of colloidal material in the soil, or to the physical state of the colloidal materials? The following investigations were directed chiefly toward the first of these questions.

The classification of soils into types is based largely on clay content, and the clay fraction, as determined by mechanical analysis, commonly contains a large part of the colloids of the soil. This denotes, of course, that fine-textured soils contain higher percentages of colloid than do sandy types. As will be brought out later in this paper, the colloidal materials of different soil types are dissimilar, however, in certain important respects. For this and perhaps other reasons which will not be discussed in this paper, it is difficult to compare one type of clay, clay loam, or silt loam, with another. There is need for accurate knowledge concerning the colloidal constituents of the important soil types.

Formerly it was believed that the so-called clay of soils is amorphous and that the exchangeable ions are held on the surface of the colloidal particles by a vaguely defined force called "adsorption." It is now virtually certain, however, that neither of these ideas is entirely sound. Hendricks and Fry (17) and Kelley, Dore, and Brown (22) showed that the inorganic colloids of many different types of soils are largely crystalline. The results of Kelley and his co-workers (22, 23, 24) and of Marshall (28) strongly indicate that the exchangeable ions are lattice constituents. These facts have a mineralogical and geological as well as an agronomic interest. It is reasonable to expect that the discovery that the inorganic colloids of many types of soil are crystalline will lead ultimately to the complete identification of the more important components of soil colloids and to a clearer understanding of their fundamental properties.

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Hendricks and Fry concluded that the colloid of the Cecil series is related to halloysite and that several other soil types contain crystalline minerals which are more like the montmorillonite-beidellite clays. Allen (1) and Bray (5, 6) concluded that certain Illinois soils contain beidellite and nontronite. More recently Jacob et al. (20) and Kelley and Dore (21) reported three different types of clay minerals in soils.

It is possible that different types of clay minerals are formed in soils at different stages in the weathering process, or, more probably, that the leaching conditions exert an important influence on the kinds of clay minerals, both as regards their formation and occurrence. Noll (31) synthesized kaolinite and montmorillonite recently. He found that when Al_2O_3 and SiO_2 are heated together under pressure in the presence of H_2O, the temperature, the pH, and the concentration of certain bases present determine the kind of mineral that is formed. If Na, K, Ca, Mg, Cs, or Be is present in a certain range of concentration, montmorillonite, which is the chief mineral of the bentonitic clays, is formed. If NaOH is the only base present and in relatively high concentration, analcite is formed, which is a mineral related to the zeolites but is not a clay mineral. On the other hand, if the same mixture of Al_2O_3 and SiO_2 is heated under pressure in the presence of either pure H_2O or an aqueous solution of HCl, but in the total absence of bases, or when the concentration of bases is very low, kaolinite is formed. These results suggest that the kind and abundance of soluble bases present in the weathering materials and the pH of the medium may exert a significant influence on the type of clay mineral that is formed.

Noll's results suggest that the soils of arid and semiarid regions and the chernozem types of soils, which occur under intermediate rainfall, will be found to contain clay minerals of the montmorillonitic type, whereas the colloids of thoroughly leached soils will more likely resemble kaolinite. Partial confirmation of this idea has already been obtained (3). As will be shown in this paper, montmorillonite is not universally present, however, in semiarid soils; neither does it necessarily follow that montmorillonitic types of clay can be converted into kaolinite or halloysite merely by prolonged leaching, although a limited amount of evidence has been obtained (25) indicating that this conversion may take place in the state of nature.

Sedleckij (36) recently reported the synthesis of montmorillonite at ordinary temperature and atmospheric pressure. He first prepared an aluminosilicate gel by bringing together solutions of sodium silicate and sodium aluminate. The gel thus obtained was then leached with *N* $MgCl_2$ until the pH of the leachate was 5.6. After virtually all the free chloride was leached out, the gel was held in a closed vessel at the temperature of the laboratory for about 4 years. Examination at the end of this period by x-ray, optical, and chemical methods showed that a crystalline product similar to montmorillonite had been formed. If this synthetic product was genuine montmorillonite, as its index of refraction suggests, then this is the first successful synthesis of a clay mineral under con-

ditions approaching those of atmospheric weathering. As will be more fully discussed in another paper, there is some doubt, however, about the mineralogical identity of this synthetic product.

METHOD OF SEPARATING THE COLLOID

The samples of colloids were separated from the coarser soil materials by the following method: About 1 kgm. of air-dried soil was dispersed in several liters of distilled water by vigorous shaking. To an occasional sample, a few drops of NH_4OH were added in order to bring about effective dispersion, but usually this was not necessary. After thorough agitation the suspensions were allowed to settle for 24 hours, then the upper 8 cm. was siphoned off. This process was repeated as many times as was necessary to obtain the desired amount of colloid. Assuming the applicability of Stokes' law to this type of material, the maximum diameter of the particles thus obtained would be approximately 1μ.

The colloidal suspensions thus obtained were coagulated with calcium chloride, and the clear supernatant liquid above the coagulated colloid was drawn off; additional amounts of calcium chloride solution were added, and the process was repeated several times. The coagulated colloidal material was then leached with distilled water until the greater part of the occluded calcium chloride was removed. Although most of the soils contained very little organic matter, the small amounts present in the colloids as separated were removed by prolonged oxidation with H_2O_2 at a temperature of approximately 80°C. After the oxidation was terminated, the samples were thoroughly leached with neutral, normal calcium acetate, then with methyl alcohol, and finally air dried. As thus prepared, the colloids were Ca-saturated. Their maximum content of carbon did not exceed 0.3 per cent, and most of the samples contained less than 0.1 per cent carbon. A special study showed that the treatment with calcium salts and H_2O_2 produced no important alteration in the clay minerals of these colloids.

With a few exceptions, all of the studies reported in this paper were made on the Ca-saturated forms of these colloids. The colloids, as separated, merely represent one fraction of the total colloid of these soils. It remains to be determined whether these samples were truly representative of the colloidal materials of these soils. The researches of Robinson and Holmes (33) and of Brown and Byers (8) suggest that the samples were faily representative.

DESCRIPTION OF THE SOILS

The *Yolo* soils are alluvial, being derived from sandstones and shales with minor admixtures of material from other sources. They rarely contain $CaCO_3$. These soils are relatively youthful, as shown by their profile characteristics. The following samples of Yolo were investigated:

Yolo silt loam, collected by C. F. Shaw from a grain field on the University Farm at Davis, Yolo County, California— No. 17557 (0–8 inches), No. 17558 (9–22 inches), No. 17559 (25–48 inches).

Yolo dark colored adobe clay, collected by S. W. Cosby from a virgin soil area 2½ miles north of Gilroy, Santa Clara County, California—No. 7083 (0–8 inches).

Yolo light brown clay loam, collected by E. E. Thomas from an unirrigated grain field ½ mile north of La Habra, Orange County, California—No. 431 (0–12 inches).

The *Vina* soils are alluvial and are derived from basic igneous rocks. In many cases the alluvium of the Vina soils has been eroded from Aiken soils areas, the Aiken being derived by residual weathering from basic igneous rocks. The Vina soils contain no $CaCO_3$. They are recent or youthful soils, as shown by the absence of pronounced profile characteristics.

Vina loam, containing moderate amounts of organic matter, collected by W. W. Weir from an unirrigated grain field 2 miles south of Chico, Butte County, California—No. 16054 (0–12 inches), No. 16055 (12–40 inches).

Vina clay loam, collected by W. W. Weir from an unirrigated area 4 miles north of Chico, Butte County, California—No. 16056 (0–12 inches).

The *Keefers* soils are relatively mature and have been derived from old valley-filling basic igneous rock materials which were probably laid down as alluvial fans during Pleistocene times. This soil series is characterized by a fairly well developed profile free from $CaCO_3$ throughout and slightly acidic. The subsoil contains much more clay than does the surface soil. The Keefers is a comparatively unimportant soil series in California, only small areas having been mapped. It was included in this study because it represents an advanced stage in the weathering of soils derived from basic igneous rock materials under moderate rainfall (20–30 inches).

Keefers gravelly loam, collected by W. W. Weir 2 miles north of South Table Mountain and 8½ miles east of Nelson, Butte County, California—No. 16057 (0–10 inches), No. 16058 (20–30 inches).

The *Sierra* soils are residual, being derived chiefly from granodiorites. As indicated by the physical characteristics of the profile, the soils of this series are fairly mature. The subsoil contains considerable accumulations of clay and in many localities rests directly on granite.

Sierra reddish brown sandy loam, collected by C. F. Shaw ½ mile southwest of Mount Orcum, El Dorado County, California—No. 16308 (½–8 inches), No. 16309 (11–20 inches), No. 16310 (22–28 inches), No. 16311 (33–43 inches).

The *Redding* soils are derived from alluvial deposits which are usually high in water-worn quartzose gravel and cobbles. The sediments are probably of Pleistocene age. This soil series is characterized by a mature profile which is definitely acidic throughout. The surface soil is reddish brown and of relatively low porosity. The B horizon is highly colloidal dense clay commonly containing many pebbles and cobbles. The B_2 horizon is, in some localities, a gray or mottled clay, as in samples 16307 and 16316. This series occurs in two distinctly different types of locality, namely, the northern part of the Sacramento Valley where the annual rainfall ranges from 20 to 30 inches, and near

San Diego where the annual rainfall is only 10 to 12 inches. Several profiles of this series were investigated.

Redding gravelly loam, collected by W. P. Kelley and S. M. Brown from an area of virgin soil on the Kearney Mesa, San Diego County, California—No. 16303 (1–15 inches), No. 16304 (20–30 inches), No. 16305 (4–18 inches), No. 16306 (18–20 inches), No. 16307 (20–37 inches).

Redding gravelly sandy loam, collected by C. F. Shaw from the S. W. ¼ Sec. 9, T 18 N, R 4 E, at Palermo, Butte County, California—No. 16314 (3–18 inches), No. 16315 (20–40 inches), No. 16316 (47–64 inches).

Redding gravelly sandy loam, collected by C. F. Shaw from the eastern part of Sec. 20, T 18 N, R 4 E, about 2 miles south of Palermo, Butte County, California, referred to hereafter as the Oroville profile—No. 16317 (2–17 inches), No. 16318 (17–40 inches).

Redding loam, collected by C. F. Shaw from the southwest corner, Sec. 14, T 20 N, R 5 W, ½ mile north of Olinda, Shasta County, California—No. 16319 (3–17 inches), No. 16320 (17–34 inches), No. 16321 (34–66 inches).

The *San Joaquin* soils are derived mainly from arkosic sediments of Pleistocene age. This series is characterized by a dense, red hardpan 1 to 2 feet thick which occurs at a depth of from 20 to 40 inches. In the virgin state much of the soil of this series has a hummocky surface and is popularly known as "hog wallow" land. The San Joaquin series of soils occurs in various parts of the San Joaquin Valley where the rainfall is only 10 to 12 inches per annum. It also occurs in certain localities in southern California where the rainfall is less than 20 inches. Soils of this series have limited agricultural value because of the nearness to the surface of the dense impervious hardpan. Good yields of various kinds of crops are often obtained, however, on San Joaquin soils.

San Joaquin loam collected by R. E. Storie from virgin grassland in the Pixley area, 2 miles northwest of Hope Schoolhouse, Tulare County, California—No. 18882 (0–10 inches), No. 18883 (22–30 inches).

San Joaquin clay loam, collected by R. E. Storie from virgin grassland 1¾ miles south of Terra Bella, Tulare County, California—No. 18884 (0–12 inches), No. 18885 (24–32 inches).

San Joaquin sandy loam, collected by R. E. Storie from virgin grassland 1½ miles west of Lindcove, Tulare County, California—No. 18888 (0–14 inches), No. 18889 (14–22 inches).

San Joaquin sandy loam, collected by C. F. Shaw from virgin grassland 1 mile south of Fairmead, Madera County, California—No. 6530 (0–10 inches).

The *Hanford* soils are developed from recently transported material derived from granitic sources. In many cases the alluvium has been eroded from areas of Holland or Sierra soils, both of which have been derived from granitic materials. The Hanford soils are youthful, showing but little evidence of segregation within the profile.

Hanford fine sandy loam, collected by C. F. Shaw ¾ mile southeast of Van Nuys in the San Fernando Valley, Los Angeles County, California—No. 7095 (0–8 inches).

Hanford sandy loam, collected by R. E. Storie from an unirrigated grain field 3 miles northeast of Delano, Kern County, California—No. 18886 (0–30 inches).

Hanford sandy loam collected by R. E. Storie from a virgin soil area 1 mile northwest of Exeter, Tulare County, California—No. 18887 (0–24 inches).

The *Ramona* soils are derived from alluvium eroded from Holland, Sierra, Vista, and Fallbrook soil areas, each of which was originally derived from granitic rocks. The Ramona series is characterized by a moderately mature profile; the subsoil contains more clay than the surface soil, and the lower part of the B horizon is usually a dense and rather compacted claypan.

Ramona loam, collected by C. F. Shaw from a grain field ½ mile northeast of La Verne, Los Angeles County, California—No. 7091 (0–6 inches).

The *Placentia* soils are derived from granitic rocks and are similar to the Ramona soils in mode of occurrence, appearance of profile, and geological history, but are more mature. The B horizon is a dense and slowly pervious, compact claypan which, however, is not cemented or impervious to water, as is the hardpan of the San Joaquin series. Placentia soils are, therefore, less mature than San Joaquin soils.

Placentia loam, collected by C. F. Shaw from a grain field 2½ miles northeast of La Verne, Los Angeles County, California—No. 7092 (0–6 inches).

The *Tujunga* soils consist of recent alluvium derived from granitic and other high-silica crystalline rocks. Soils of this series commonly contain many large stones and boulders of granite washed down from higher elevation along with the finer-grained materials. They are very immature soils, showing virtually no segregation within the profile.

Tujunga fine sandy loam, collected by C. F. Shaw from a geologically recent alluvial fan 1 mile southeast of Lankershim, Los Angeles County, California—No. 7094 (0–8 inches).

The *Madera* soils are derived from alluvium of mixed geological origin, but probably chiefly granodiorite. The granitic sediments were probably deposited in Pleistocene times, but subsequently more or less alluvium has been mixed with the older sediments, giving to this series a somewhat mixed origin. It occurs under an annual rainfall of 10 to 15 inches. The profile is usually mature. The subsoil is more dense than the surface soil and rests on a well-developed red hardpan which is usually slightly calcareous. This hardpan is less dense than that characterizing the San Joaquin series.

Madera clay loam, collected by C. F. Shaw from a virgin area in Sec. 15, T 85, R 15 E, near Madera, Madera County, California—No. 6528 (0–10 inches).

The *Tule* soils occur on the high terraces along the Tule River in Tulare County, California. Apparently derived from relatively old sediments of granitic origin, they are similar to the soils of the Redding series except that the pH is usually higher. In the soil survey report of this area, soon to be issued, the Tule soils will be shown as members of the Redding series. The surface of the Tule soils is characterized by a hummocky, hog wallow undulation suggestive of that of the San Joaquin soils. The subsoil is comparatively heavy and rests on dense hardpan, similar to that of the Redding.

Tule gravelly clay loam, collected by R. E. Storie, 2½ miles southwest of Springville, Tulare County, California—No. 18890 (0–15 inches), No. 18891 (15–19 inches).

The *Maxwell* soils are black adobe clays derived from serpentine rocks. They are usually recently deposited heavy clay and may be several feet deep but show only slight evidence of segregation within the profile. There are many comparatively small areas of these soils in California. The Maxwell series is characterized by extreme infertility. The area of Maxwell adobe clay sampled has been repeatedly seeded to barley, but crop failure has always resulted. The native vegetation is predominantly anise; near-by soils of other types were originally covered with various natural grasses.

Maxwell adobe clay, collected by C. F. Shaw and W. P. Kelley from Wooden Valley, Napa County, California—No. 17399 (0–18 inches).

CHEMICAL ANALYSIS

The results of fusion analysis of the colloids are given in a series of tables. Since the colloids were Ca-saturated, the amounts of Mg, K, and Na found represent nonreplaceable forms of these elements. In some of the samples a small percentage of the Ca was also nonreplaceable, although the greater part was replaceable.

Table 1 shows the composition of the Yolo soil colloids. It will be noted that the Yolo silt loam colloid from Davis, California, is remarkably uniform in composition from the surface of the soil down to a depth of 48 inches. The MgO content is comparatively high, and K_2O and Na_2O are low. As has been mentioned, these bases were present in the samples in nonreplaceable forms, whereas the greater part of the CaO was replaceable. The content of SiO_2, Al_2O_3, and Fe_2O_3 was approximately the same in each of the samples from Davis. Apparently, the same kind of colloidal material occurs throughout this profile. The Yolo adobe clay colloid from Gilroy (No. 7083) contained slightly less SiO_2 and more Fe_2O_3 and K_2O than the Davis colloids. Otherwise, they are similar in composition. On the other hand, colloid 431 from La Habra contains considerably less MgO, Al_2O_3, and Fe_2O_3, and relatively more SiO_2 than the other Yolo clay colloids. As will be shown later, the optical properties of this colloid differ somewhat from those of the Davis and Gilroy samples.

Although the authors of this paper do not attach great significance to the molecular ratios of materials of this sort, the data assembled in table 2 show that the SiO_2-Al_2O_3 and SiO_2-R_2O_3 ratios are relatively high in the Yolo clay colloids. No significant differences in these ratios were found in the colloids from the different horizons of the Davis Yolo silt loam, the SiO_2-Al_2O_3 ratio being approximately 4 and the SiO_2-R_2O_3 ratio about 3. The Gilroy sample gave somewhat lower molecular ratios and the La Habra sample definitely higher ratios than the Davis colloids. The base-exchange capacity of the Yolo clay colloids, as determined by the ammonium acetate method, was

comparatively high. The fact that the content of replaceable Ca agrees closely with the NH_4 absorbed from ammonium acetate, both in this and all other series reported in this paper, indicates that the samples were truly Ca-saturated.

Chemical analysis of the Vina samples (table 3) shows certain striking differences which distinguish these colloids from the Yolo clay colloids reported

TABLE 1

Chemical analysis of Ca-saturated Yolo colloids

SAMPLE NUMBER	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	P_2O_5	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
431	48.34	16.92	9.25	0.83	0.04	0.27	2.13	2.99	1.97	0.66	18.20	101.60
7083	40.53	18.65	12.30	1.05	0.05	0.28	2.64	4.26	1.57	0.52	18.00	99.85
17557	43.92	18.65	10.22	0.24	0.11	0.32	1.72	4.59	0.47	0.45	19.00	99.69
17558	43.84	18.13	10.94	0.27	0.11	0.32	1.73	4.72	0.48	0.46	19.30	100.30
17559	44.71	18.25	10.72	0.38	0.08	0.26	1.80	4.85	0.52	0.46	19.00	101.03

TABLE 2

Molecular ratios and base-exchange capacity of Yolo colloids

SAMPLE NUMBER	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{R_2O_3}$	BASE-EXCHANGE CAPACITY		pH OF ORIGINAL SOIL
			Replaceable Ca	Absorbed NH_4	
			m.e.	*m.e.*	
431	4.85	3.60	67.6	68.1	6.90
7083	3.69	2.61	66.9	67.0	6.98
17557	4.00	2.97	56.5	56.2	7.10
17558	4.12	2.98	57.7	58.5	7.11
17559	4.16	3.03	56.4	56.9	7.10

TABLE 3

Chemical analysis of Ca-saturated Vina colloids

SAMPLE NUMBER	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	P_2O_5	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
16054	40.59	22.84	10.95	0.80	0.04	0.46	2.10	0.55	1.05	0.14	20.35	99.87
16055	40.11	23.15	11.48	0.79	0.06	0.29	2.10	0.55	0.94	0.23	19.77	99.47
16056	40.02	20.61	10.50	0.56	0.04	1.19	1.65	1.23	0.48	0.41	23.20	99.89

in table 1. These differences are chiefly in the much lower MgO and the higher Al_2O_3 content of the Vina colloids, the latter being reflected, of course, in the ratios of SiO_2 to Al_2O_3 and SiO_2 to R_2O_3 (compare tables 2 and 4). Whereas the SiO_2-Al_2O_3 ratio is approximately 4 in the Yolo clay colloids, it is more nearly 3 in the Vina colloids. The base-exchange capacities of the Yolo and Vina colloids, however, are not significantly different.

Although both the Keefers and the Vina soils have been derived from basic igneous rocks, the chemical analyses of the colloids show certain differences (compare tables 3 and 5). The Keefers clay colloids contain less SiO_2 and more Al_2O_3 and Fe_2O_3 than the Vina. These differences are reflected in the molecular ratios (compare tables 4 and 6). The base-exchange capacity of the Keefers clay colloids is only slightly more than half that of the Vina.

The Sierra clay colloids were found to contain substantially more Al_2O_3 and correspondingly less Fe_2O_3 than the Keefers (compare tables 5 and 7).

TABLE 4

Molecular ratios and base-exchange capacity of Vina colloids

SAMPLE NUMBER	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{R_2O_3}$	BASE-EXCHANGE CAPACITY		pH OF ORIGINAL SOIL
			Replaceable Ca	Absorbed NH_4	
			m.e.	*m.e.*	
16054	3.02	2.25	64.2	61.7	6.68
16055	2.94	2.24	65.0	64.0	6.65
16056	3.30	2.49	58.0	60.0	6.62

TABLE 5

Chemical analysis of Ca-saturated Keefers colloids

SAMPLE NUMBER	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	P_2O_5	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
16057	36.43	25.97	13.76	1.12	0.09	0.92	0.95	0.65	1.08	0.35	18.98	100.30
16058	36.14	26.28	13.68	1.28	0.20	1.08	1.00	0.65	0.77	0.56	17.95	99.59

TABLE 6

Molecular ratios and base-exchange capacity of Keefers colloids

SAMPLE NUMBER	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{R_2O_3}$	BASE-EXCHANGE CAPACITY		pH OF ORIGINAL SOIL
			Replaceable Ca	Absorbed NH_4	
			m.e.	*m.e.*	
16057	2.38	1.78	34.7	35.1	6.69
16058	2.34	1.76	34.6	35.5	6.66

The composition was similar throughout the depth sampled. The content of SiO_2 and MgO was somewhat higher in the Sierra than in the Keefers. The SiO_2-Al_2O_3 ratios were approximately 2 and the SiO_2-R_2O_3 ratios about 1.70 (table 8). The base-exchange capacity was low, being approximately one-half that of the Keefers colloids.

Tables 9 and 10 show that the composition of the different samples of Redding clay colloids varies considerably. The SiO_2-Al_2O_3 ratio varied from 2.02 to 3.47, and the SiO_2-R_2O_3 ratio from 1.71 to 2.65. The base-exchange capacities were found to be roughly proportional to the SiO_2-Al_2O_3 ratios.

The Olinda Redding clay colloids are not significantly different in mass composition from the Sierra colloids. All the other Redding samples contain

TABLE 7

Chemical analysis of Ca-saturated Sierra colloids

SAMPLE NUMBER	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	P_2O_5	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
16308	38.68	31.47	10.04	0.66	0.14	0.42	0.61	1.96	0.86	0.46	13.95	99.25
16309	38.93	32.69	9.72	0.76	0.08	0.27	0.49	1.52	0.84	0.36	13.30	98.96
16310	39.12	33.58	9.08	0.60	0.04	0.29	0.45	1.05	0.52	0.33	15.30	100.36
16311	39.78	32.93	9.20	0.75	0.04	0.34	0.45	1.16	0.18	0.27	15.10	100.20

TABLE 8

Molecular ratios and base-exchange capacity of Sierra colloids

SAMPLE NUMBER	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{R_2O_3}$	BASE-EXCHANGE CAPACITY		pH OF ORIGINAL SOIL
			Replaceable Ca	Absorbed NH_4	
			m.e.	*m.e.*	
16308	2.09	1.75	21.9	22.7	5.81
16309	2.03	1.70	18.8	19.6	5.48
16310	1.98	1.69	16.2	16.0	6.00
16311	2.06	1.74	16.0	16.4	6.65

TABLE 9

Chemical analysis of Ca-saturated Redding soil colloids

SAMPLE NUMBER	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	P_2O_5	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
16303	43.27	30.69	8.12	0.45	0.01	0.36	0.55	1.09	0.23	0.22	15.10	100.09
16304	44.56	29.19	8.40	0.51	0.1	0.35	0.82	0.78	0.29	Tr.	16.20	101.10
16305	42.93	28.57	10.55	1.08	0.02	0.36	0.63	0.87	0.82	0.67	13.29	99.79
16306	42.77	29.50	7.85	0.86	Tr.	0.36	0.67	0.80	0.45	0.32	16.16	99.74
16307	43.36	30.23	6.96	0.68	Tr.	0.37	0.90	0.77	0.40	0.39	15.52	99.58
16314	42.80	26.89	9.75	0.48	0.90	0.42	1.10	1.12	0.11	0.21	17.20	100.08
16315	43.72	22.38	9.67	0.45	0.10	0.29	1.70	1.93	0.13	0.16	18.90	99.43
16316	43.52	21.35	10.20	0.40	0.01	0.25	1.55	1.66	0.16	0.24	20.10	99.44
16317	40.47	29.15	8.52	0.57	0.17	0.40	0.90	1.27	0.19	0.25	17.90	99.79
16318	40.87	27.64	9.96	0.45	0.07	0.48	0.99	1.16	0.15	0.19	17.80	99.76
16319	39.68	32.52	8.76	0.30	0.06	0.45	0.56	1.18	0.12	0.19	16.40	100.22
16320	39.40	32.94	9.10	0.39	0.02	0.42	0.50	0.89	0.13	0.23	16.00	100.02
16321	39.24	32.98	8.57	0.45	0.02	0.44	0.57	0.89	0.16	0.23	16.30	99.85

somewhat more SiO_2 and less Al_2O_3 than the Sierra. It will be noted that the colloid of the Redding profile at Palermo differs markedly in composition from the Redding samples of other localities. As will be brought out in later

sections of this paper, the optical and x-ray investigations also showed that this profile is different from the other Redding soils.

The Redding clay colloid from Oroville profile is remarkably similar to that of the Kearney Mesa. This is surprising because of the difference in the annual rainfall of these areas, namely, 20 to 30 inches at Oroville and only 10 to 12 inches on the Kearney Mesa. It is also interesting to note that the

TABLE 10

Molecular ratios and base-exchange capacity of Redding colloids

SAMPLE NUMBER	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{R_2O_3}$	BASE-EXCHANGE CAPACITY		pH OF ORIGINAL SOIL
			Replaceable Ca	Absorbed NH_4	
			m.e.	*m.e.*	
16303	2.39	2.04	21.2	23.2	5.51
16304	2.59	2.19	30.5	34.6	4.92
16305	2.55	2.07	23.1	22.9	5.40
16306	2.47	2.11	23.5	23.9	5.00
16307	2.44	2.13	31.9	32.0	4.82
16314	2.67	2.20	38.9	39.4	6.70
16315	3.32	2.60	60.2	59.2	5.75
16316	3.47	2.65	55.4	55.5	5.75
16317	2.36	1.99	31.9	30.9	5.50
16318	2.51	2.04	35.4	35.5	5.35
16319	2.07	1.77	19.9	19.7	5.62
16320	2.03	1.73	18.7	18.2	5.28
16321	2.02	1.71	19.2	18.5	5.05

TABLE 11

Chemical analysis of Ca-saturated San Joaquin colloids

SAMPLE NUMBER	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	P_2O_5	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
18882	46.51	23.92	9.76	1.00	0.18	0.26	1.17	1.54	1.61	0.40	14.20	100.55
18883	46.49	23.18	10.37	1.10	0.13	0.26	1.30	1.46	1.26	0.34	14.26	100.15
18884	48.04	20.41	10.35	1.30	0.16	0.19	1.23	2.11	1.44	0.46	14.06	99.75
18885	48.31	21.59	10.40	1.10	0.13	0.16	1.18	3.02	1.56	0.46	13.00	100.91
18888	44.96	23.35	10.69	1.20	0.24	0.18	1.27	2.73	1.84	0.19	14.23	100.88
18889	45.75	25.70	8.96	1.30	0.17	0.18	1.11	2.72	1.50	0.30	14.35	102.04
6530	44.62	23.74	9.92	0.54	0.05	0.51	0.76	2.33	1.43	Tr.	15.96	99.86

colloid of the A horizon of the Kearney Mesa samples has lower base-exchange capacity than that of the B horizon. The same is true of the Oroville and Palermo samples, but it is not true of those from Olinda.

Analysis shows that the San Joaquin soil colloids from the different profiles (table 11) are remarkably similar in elementary composition and that the A and B horizons are also similar in composition. The samples from the Pixley area, Terra Bella, and Lindcove contain more calcium than that from

Fairmead. It is interesting to note that the SiO_2-Al_2O_3 and SiO_2-R_2O_3 ratios are comparatively high (see table 12). The base-exchange capacity was approximately the same in all the samples except that from Fairmead, which was comparatively low, despite the fact that its molecular ratios are relatively high. This shows that there is no certain relationship between base-exchange capacity and the ratio of SiO_2 to Al_2O_3 or SiO_2 to R_2O_3.

TABLE 12

Molecular ratios and base-exchange capacity of San Joaquin colloids

SAMPLE NUMBER	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{R_2O_3}$	BASE-EXCHANGE CAPACITY		pH OF ORIGINAL SOIL
			Replaceable Ca	Absorbed NH_4	
			m.e.	*m.e.*	
18882	3.31	2.63	43.1	43.9	7.21
18883	3.41	2.65	47.2	48.0	8.26
18884	4.00	3.03	43.6	44.0	6.91
18885	3.81	2.92	43.7	44.3	8.11
18888	3.27	2.53	40.0	40.5	7.41
18889	3.02	2.47	39.5	40.0	7.21
6530	3.20	2.53	27.0	27.6	7.17

TABLE 13

Chemical analysis of Ca-saturated Hanford colloids

SAMPLE NUMBER	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	P_2O_5	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
7095	42.41	20.33	13.12	0.30	0.09	0.38	1.94	3.00	0.60	Tr.	17.81	99.98
18886	47.22	23.63	10.84	0.40	0.13	0.26	1.59	3.32	1.77	0.46	14.04	103.66
18887	44.35	21.83	11.34	0.80	0.17	0.24	1.51	3.15	2.02	0.34	14.11	99.86

TABLE 14

Molecular ratios and base-exchange capacity of Hanford colloids

SAMPLE NUMBER	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{R_2O_3}$	BASE-EXCHANGE CAPACITY		pH OF ORIGINAL SOIL
			Replaceable Ca	Absorbed NH_4	
			m.e.	*m.e.*	
7095	3.55	2.51	47.4	47.9	7.70
18886	3.41	2.63	57.5	56.0	7.83
18887	3.45	2.59	45.7	46.5	8.11

Chemical analyses of the Hanford clay colloids (table 13) gave results similar to those of the San Joaquin colloids reported in table 11. This similarity is further shown by their molecular ratios and base-exchange capacities (compare tables 12 and 14). The SiO_2-Al_2O_3 ratio of the Hanford colloids was approximately 3.50, the SiO_2-R_2O_3 ratio about 2.60, and the base-exchange capacity approximately 50 m.e. per 100 gm.

Since only a single sample each of the Ramona, Placentia, Tujunga, Madera, and Maxwell soils was investigated it is not necessary to discuss the results in detail. It will be noted, however, that the Tujunga, which is classified as the youngest member of the San Joaquin family of soils, contains colloid of composition similar to that of the San Joaquin series, which is the oldest member of this family (compare tables 11 and 15). On the other hand, the Ramona and Placentia soils are classified as intermediate members of the San Joaquin family, but the chemical analysis of the colloids of these two samples differs considerably from that of both the Tujunga and the San Joaquin soils. The

TABLE 15

Chemical analysis of Ca-saturated colloids from soils of various series

SAMPLE NUMBER	SERIES	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	P_2O_5	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
		per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
7091	Ramona	41.12	27.51	10.88	....	....	....	0.89	2.54	0.80	Tr.	15.42	99.16
7092	Placentia	39.62	29.85	8.60	0.35	0.02	0.34	0.69	2.73	0.76	Tr.	15.98	98.94
7094	Tujunga	43.75	21.20	9.92	0.45	0.08	....	2.21	2.58	0.60	0.20	18.40	99.39
6528	Madera	41.96	23.35	10.60	0.38	0.06	0.41	1.36	3.17	0.50	Tr.	17.62	99.41
18890	Tule	43.60	19.20	13.02	1.00	0.12	0.16	1.46	1.97	1.26	0.19	16.36	98.34
18891	Tule	43.43	24.00	9.44	1.20	0.04	0.21	1.72	1.95	0.30	0.19	18.07	100.55
17399	Maxwell	44.08	15.85	9.20	0.16	0.04	0.11	1.82	10.25	0.17	0.16	17.80	99.64

TABLE 16

Molecular ratios and base-exchange capacity of various soil colloids

SAMPLE NUMBER	SERIES	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{R_2O_3}$	BASE-EXCHANGE CAPACITY		pH OF ORIGINAL SOIL
				Replaceable Ca	Absorbed NH_4	
				m.e.	*m.e.*	
7091	Ramona	2.54	2.03	27.8	27.7	7.13
7092	Placentia	2.26	1.91	24.7	24.8	7.11
7094	Tujunga	3.50	2.70	56.5	57.2	7.57
6528	Madera	3.04	2.36	45.7	46.1	....
18890	Tule	3.86	2.70	42.0	43.4	7.58
18891	Tule	3.03	2.45	55.1	56.4	7.07
17399	Maxwell	4.74	3.45	63.0	65.1	6.94

Madera clay colloid is similar to that of the San Joaquin both in elementary composition and in base-exchange capacity (compare tables 12 and 16). Before definite conclusions can be drawn concerning the relations between composition and properties of colloid and maturity of profile, it will be necessary to investigate a considerable number of profiles of these and other soil series. The data presented herein, although not conclusive, do not indicate any significant relation between quality of colloids and maturity of profile.

Analyses of the colloid from the Tule soil profile show that it is similar to the San Joaquin colloid in composition and base-exchange property.

The Maxwell adobe clay colloid is strikingly different from any other soil colloid reported in this paper. The content of Al_2O_3 is low and the MgO very high. The base-exchange capacity of this sample was relatively high, being approximately the same as that of the Yolo, Vina, and the Palermo samples of the Redding. The SiO_2-Al_2O_3 and SiO_2-R_2O_3 ratios are high, because of the low content of Al_2O_3. The composition of this colloid is similar to that of serpentine soils from other localities in the United States, as reported by Robinson, Edgington, and Byers (32).

DEHYDRATION INVESTIGATIONS

Samples of the colloids were first brought to comparable moisture conditions by exposing them to an atmosphere of known moisture content until their weights were constant. The water vapor pressure used was that of a 52 per cent solution of sulfuric acid at a temperature of 25°C., which roughly corresponds to the average minimum atmospheric moisture at Riverside, California, where this investigation was made. The dehydrations were made against an atmosphere of approximately constant moisture content, provided by passing a current of air first through 52 per cent sulfuric acid (by volume), then through the electric furnace in which the samples were heated. The samples were held in the furnace at each temperature until constant in weight. The results are shown by a series of graphs, only typical representatives of the different types of the curves being shown. Except as indicated below, the several horizons of each soil type gave almost identical dehydration curves.

The dehydration curves of the different Yolo clay colloids have a similar wavelike shape (fig. 1). Those for the Davis samples resemble the curves for montmorillonite and beidellite [see Kelley, Jenney, and Brown (24)]. Attention is directed to the relatively large water loss at 100° and 150°C.

The curves for the Vina and the Keefers clay colloids (fig. 2) are approximately parallel and show deflections between 300° and 400°C. These colloids seem to resemble finely ground kaolinite and halloysite. As will be shown later, all the colloids reported in this paper are definitely crystalline. Either the crystals of the Vina and Keefers samples are extremely small, however, or else they contained considerable amorphous material. Special attention is drawn to that fact that at the lower temperatures the water losses of Vina colloid 16055 were similar to those of the Yolo samples, whereas those of the Keefers sample 16058 were substantially less. In each case the loss was roughly proportional to the base-exchange capacity.

The Sierra and most of the Redding clay colloids (fig. 3) gave remarkably similar dehydration curves, which closely approach that of the Cecil clay colloid from the Piedmont Plateau, as reported by Kelley and his co-workers (24, 25). Pronounced deflections in the curves were noted between 300° and 400°C. These curves strongly suggest halloysite or kaolinite (34, 35). The Kearney Mesa samples from the Redding soils and certain of the samples from northern California proved to be almost identical. On the other hand,

the curves for the B and C horizons of the Redding at Palermo (fig. 4), although of the same general shape, nevertheless show that these colloids contain considerably more low-temperature water. The evidence is that these samples contain considerably greater percentages of nonkaolinitic clay minerals than do the other Redding samples. The colloid of the A horizon of the Palermo Redding soil differs from that of the B horizon in that the low-temperature water of the latter was the greater. Otherwise their dehydration curves were similar.

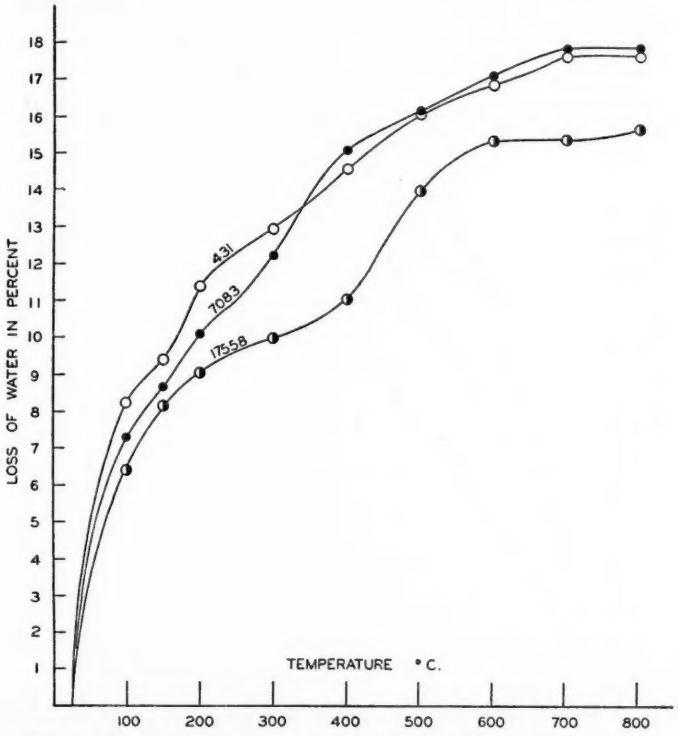

FIG. 1. DEHYDRATION CURVES OF YOLO COLLOIDS, 431, 7083, AND 17558

Although certain features of the Tule soil are suggestive of the San Joaquin series, the dehydration curves were remarkably like those of the Redding Palermo clay colloids.

The San Joaquin and Hanford clay colloids (fig. 5) gave dehydration curves of approximately the same shape, both showing pronounced deflections. These curves differ from those of the Sierra and Redding chiefly in that the deflections occur at higher temperatures. This indicates a different type of

clay mineral. As will be shown later, the Sierra and most of the Redding samples are definitely kaolinitic, whereas the San Joaquin and Hanford clay colloids resemble illite (13).

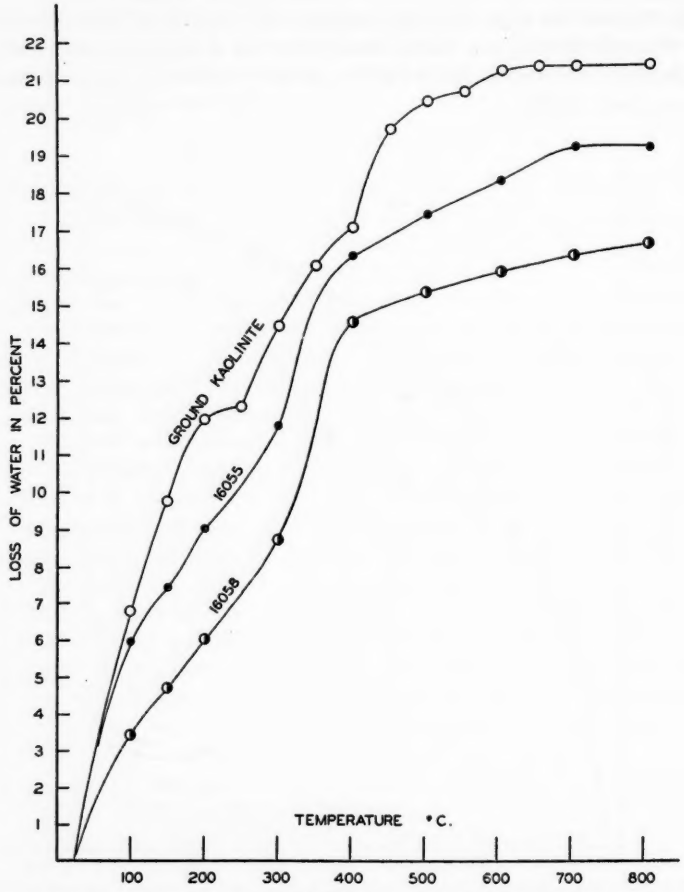

FIG. 2. DEHYDRATION CURVES OF VINA (16055) AND KEEFERS (16058) COLLOIDS AND OF FINELY GROUND KAOLINITE

RESULTS OF MICROSCOPICAL STUDY

The colloid samples discussed in the foregoing sections of this paper were studied in oil and water mounts with a Leitz CM petrographical microscope, using artificial light and a daylight filter. The series of oils used had indexes spaced at intervals of approximately .005, and were checked two or three times by means of a Spencer Abbe refractometer. The refractometer was

tested with standard glass plates of both high and low indexes and was found to have an accuracy beyond our needs.

In consequence of evaporation and the other treatments, the minute particles of the original colloidal suspension in almost all the samples had gathered into relatively large optical units commonly 0.1 mm. and rarely 1 mm. in diameter. These units were recognized by their double refraction. Hendricks and Fry (17) have briefly described the same effect, and Grim (12) has discussed it more fully. The indexes of refraction of these compound par-

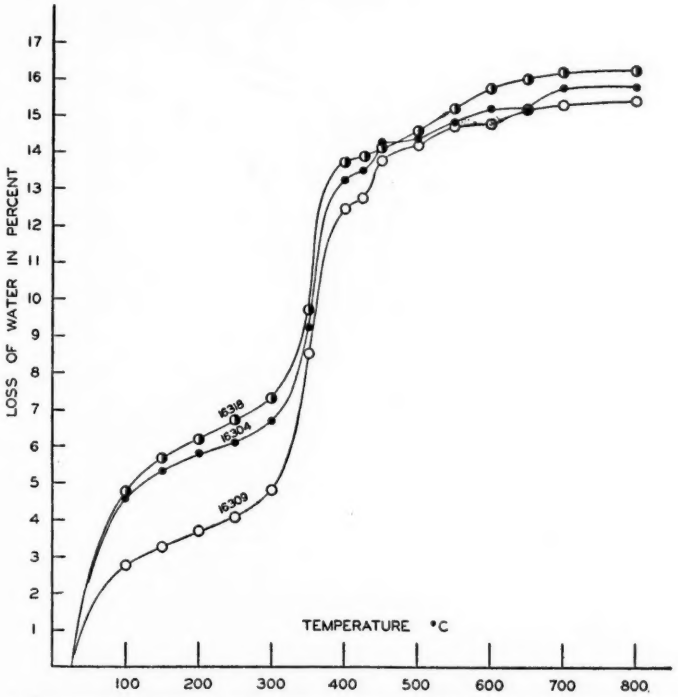

FIG. 3. DEHYDRATION CURVES OF REDDING COLLOIDS (16304 FROM SOUTHERN CALIFORNIA AND 16318 FROM NORTHERN CALIFORNIA) AND SIERRA COLLOID 16309

ticles were determined by the method of central illumination (26), the usual corrections for temperature being made.

The clay aggregates have a smooth jellylike appearance under the microscope, but virtually all of them were more or less platy or flaky. Wherever determinable, the optical character was found to be negative, with the acute bisectrix perpendicular to the plates or within 30° of that position. The poor interference figures given by the samples were uniaxial or biaxial with small optic angles (2V).

Rigorous study of the probable error of the index determinations was not made. Almost all the determinations, however, were repeated once, and some of them many times. Concurrent studies on bentonite also gave information concerning the range of experimental error. The maximum variations for single samples found in the earlier part of this study were as follows: soil clay aggregates, alpha .013, beta .012, gamma .010; Ca-saturated bentonite

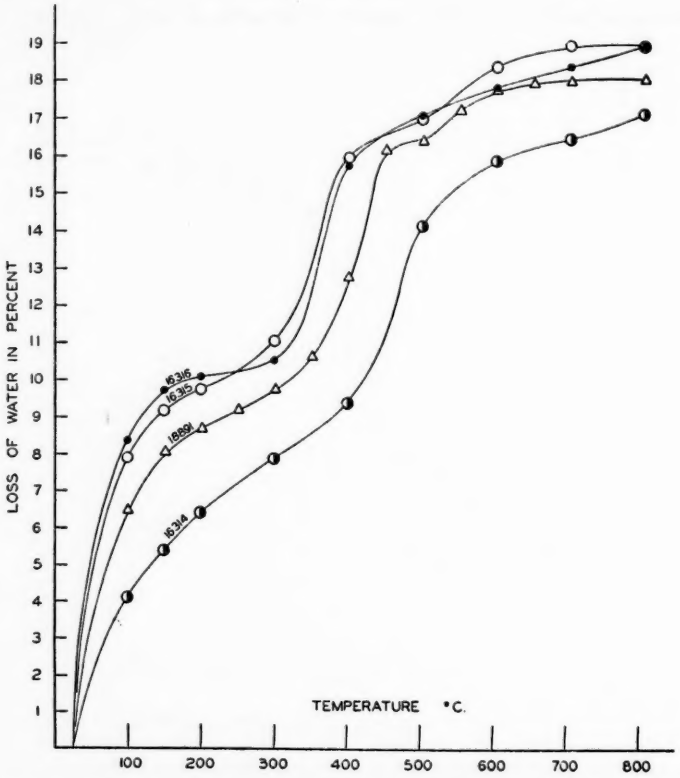

FIG. 4. DEHYDRATION CURVES OF REDDING COLLOIDS FROM PALERMO, 16314 (3–18 INCHES), 16315 (20–40 INCHES), AND 16316 (47–64 INCHES), AND OF TULE COLLOID 18891 (15–19 INCHES)

colloids, alpha .030, beta .022, gamma .026. Variations in moisture content were at once suspected of being involved; consequently, a sample of bentonite from Otay, California, one of the most variable bentonites, was exposed over water in a desiccator for 56 hours and also over concentrated H_2SO_4. Gamma over water was found to be 1.470 and over H_2SO_4 1.520.

The earlier optical study was carried out in Riverside during the summer of

1932 when the relative humidity at 8:30 a.m. ranged from 26 to 94, and averaged 69. Later work, from September, 1932, to September, 1934, was on samples exposed in 1- to 2-mm. films over 52 per cent H_2SO_4, giving a humidity of approximately 30. Every sample was determined at least once over 52 per cent H_2SO_4, at room temperatures ranging from 20° to 25°C.

The indexes for Ca-saturated clay aggregates, as given in table 17, are thought to be accurate in most cases to ±.003. The colloids with high indexes and low double refraction gave less satisfactory results, accurate to perhaps

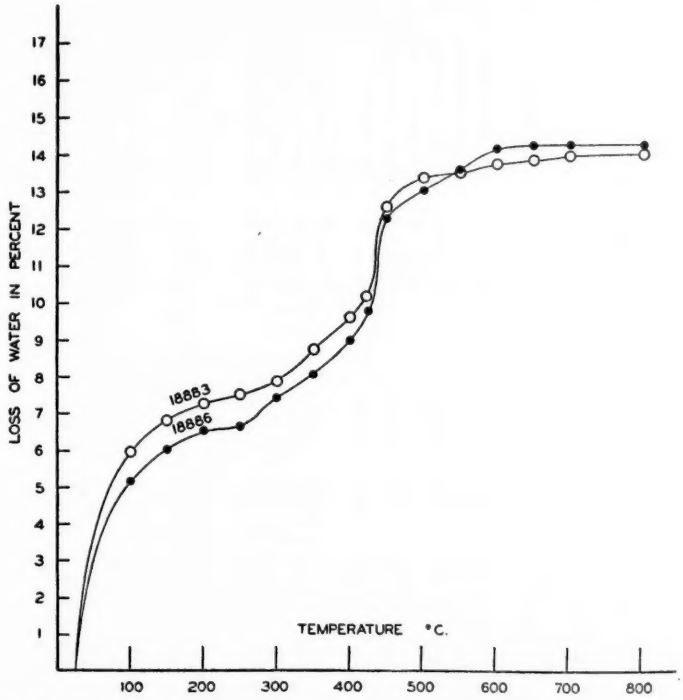

FIG. 5. DEHYDRATION CURVES OF SAN JOAQUIN COLLOID 18883 AND HANFORD COLLOID 18886

±.005. Since the Keefers samples 16057 and 16058 showed poorly formed flakes or deep color or both, the determinations in these cases are still more doubtful, with an accuracy of perhaps ±.010. The various errors are thought to be due (a) to residual moisture differences caused by variations in temperature and hence of water vapor pressure and also to incomplete equilibrium with the atmosphere of the desiccator in the lower parts of the samples, thin though they were, and (b) to innate difficulties in the index determinations, due largely to the abundant inclusions mentioned below. The determination of alpha is most difficult because the flakes must be on edge.

TABLE 17

Optical properties of Ca-saturated clay aggregates from soils

SERIES	LABORATORY NUMBER	DR*	INDEXES OF REFRACTION			$\gamma-\alpha$	2V†	EXTINCTION	NOTES
			Alpha	Beta	Gamma				
		per cent							
Tujunga	7094	100	1.553	1.569	1.569	0.016		0–35°	Irregular plates
Hanford	7095	100	1.567	1.580	1.580	0.013		0°	Indexes variable
Ramona	7091	100	1.581	1.591	1.591	0.010		0° approx.	Indexes variable
Placentia	7092	100	1.574	1.587	1.587	0.013		0–20°, 38°	Fair plates
San Joaquin	6530	100	1.563	1.576	1.579	0.016		0°	Rather poor plates
Madera	6528	100	1.551	1.569	1.569	0.018	Near 0°	0–30°	Good plates and ext.
Vina	16054	33	1.568		1.573	0.005		0° usually	67% isotropic, n 1.570
	16055	100–	1.564	1.572	1.572	0.008		0° usually	Rarely (–) elong.
	16056a	100?	1.571		1.574	0.003		0° usually	Rarely (–) elong.
	16056b	100	1.564	1.582	1.583	0.019		0° usually	Much rarer than 16056a
Keefers	16057	Little	n = 1.60+; no large grains						
	16058	Little	n = 1.610 ± 0.010; no large birefringent grains except mica (?) shreds						
Yolo A	7083	100	1.567	1.586	1.587	0.020		0–15°	Rarely lower indexes
A	17557	100	1.551	1.572	1.574	0.023		0° usually	
B	17558	100	1.556	1.574	1.576	0.020		0° usually	Very good plates
C	17559	100	1.555	1.573	1.574	0.019		0°	
A	431	100	1.554	1.569	1.569	0.015		0° usually	Indexes vary; rare (–) elong.; impure

Redding	A	16303	100	1.584	1.593	1.594	0.010	Near 0°	0° up	Good plates
	B	16304a	100−	1.569	1.579	1.580	0.011		0°–30°	Good plates; "rare (−) elong."
	B	16304b	100	1.557±		1.573±	0.016			Much rarer than 16304a
	A	16305	100−	1.593		1.600	0.007		0–40°	Also lower indexes
	B_1	16306	100−	1.584	1.594	1.594	0.010		0°	Like 16305
	B_2	16307	100	1.557	1.569	1.569	0.012		0–28°	Like 16304
Redding	A	16314	100−	1.575	1.583	1.583	0.008		0°	Poor flakes
	B_1	16315	100	1.535	1.548	1.550	0.015		0–40°	Good plates; also some with higher indexes, γ = 1.558
	B_2	16316	100	1.533	1.550	1.553	0.020		0–30°	Indexes vary
	A	16317	100?	1.598		1.601	0.003		0?–30°	Poor flakes; tests vague
	B	16318	100	1.588		1.596	0.008		0–40°	Poor flakes; indexes vary
	A	16319	100?	1.601+		1.604+	0.003			Poor flakes
	B_1	16320	100?	1.598	1.604	1.604	0.006		0°?	Fair flakes
	B_2	16321	100	1.592	1.598?	1.600	0.008		0°?	Fair flakes
Sierra		16308	100	1.590	1.597	1.600	0.010		0–30°	Micaceous inclusions
		16309	100−	1.592		1.604	0.012		0–30°	Micaceous inclusions
		16310	100	1.590	1.602	1.604	0.014		0–10°	Micaceous inclusions
		16311	100	1.592		1.603	0.011		0–15°	Micaceous inclusions
Maxwell		17399	100	1.544	1.560	1.560	0.016	0°+	0–20°	Indexes vary; γ 1.556–1.562

* DR = Double refraction.

† 2V given only for the rare cases in which fairly good interference figures were observed.

Double refraction was calculated from the indexes, but not entirely without check. In determining the indexes, the double refraction indicated by the interference colors was kept in mind. In a few cases it was possible to calculate the double refraction from the width of a flake and its intereference tint when on edge. For example, Redding colloid 16303 was found to have $\gamma - \alpha = 0.010$ both by the difference between the measured indexes and by calculation from the interference tint. For the major part of Redding 16304 the indexes indicated $\gamma - \alpha = 0.011$, and a flake on edge gave an interference tint corresponding to $\gamma - \alpha = 0.009$.

In general the double refraction as given, even where a nearly pure clay mineral is concerned, may be too low, because of optical compensation in the compound flakes, or too high, because of the addition of form double refraction to the proper double refraction of the clay mineral.

The flaky aggregates of the different clays ranged from pale yellow-brown to very dark brown in color. No pleochroism was certainly observed. In general, the darker is the color, the higher are the indexes and the lower is the double refraction, but this is only a very rough correlation.

Extinction was commonly somewhat vague and undulatory, but in some of the paler, more definitely platy clays it was perfectly sharp. Where the extinction was most definite, the double refraction was found to be highest, and this suggests that the differences in double refraction given in table 17 are exaggerated, the lower values being in part due to compensation between differently oriented portions of a given flake. The fact that more or less complete extinction can be obtained, however, indicates that in such cases the various parts of a single flake occur in approximately similar orientation, especially with respect to the X optical direction (alpha index).

The large, birefringent optical units thus far discussed are crowded with innumerable minute inclusions. These are usually irregularly equidimensional, but inclusions were found in the shape of definite rods and flakes from 3 to 15 μ in diameter or length. Some of the apparent inclusions may have been mere cavities, analogous to the systems of tubes and bubblelike spots such as have been observed in the mineral anauxite from Ione clay of California. But the evidence indicates that the minute inclusions in the soil clays were chiefly solid. Many of them were birefringent. Furthermore, the inclusions stand out from the host grains in high relief, indicating that they are of different index and density and presumably of different composition.

Some of the minute inclusions have been identified by the use of an oil immersion objective and 20 x ocular. Limonite or similar iron oxide is abundant, and rutile, zircon (?), quartz, muscovite, bleached biotite (?), and other minerals were also present. Color and relief suggest that a large part of the inclusions may have been iron oxide. The minute inclusions were relatively scarce in the Sierra clay colloids, and at least half of those present were birefringent. The greater part of the birefringent inclusions are yellow flakes, thought to be weathered mica.

The Keefers samples were unique among those studied, in that they yielded no large birefringent units. The samples were composed entirely of minute grains, most of which showed no birefringence even under the oil immersion objective. Birefringent rods and needles of rutile up to 15 μ in length were recognized in these samples, and other minute prisms of paler color were seen which may have been zircon or possibly some other mineral. The isotropic portion of the samples included brown grains of high index which are considered to be limonite, and by far the greater part of the Keefers samples consists of minute, brownish, angular, isotropic grains which individually showed high relief in the media used, but which in aggregates seemed to have the indexes listed in table 17.

Study of natural colloids. For comparison with the Ca-saturated form of these colloids, a few samples of untreated aqueous suspensions, obtained directly from the original soils, were dried below 100°C. and studied in oils. These and the Ca-saturated materials yielded almost identical results. For example, the Yolo clay 7083, the one most thoroughly investigated in the untreated state, gave values of gamma ranging from 1.583 to 1.588 as compared with 1.587 for the Ca-saturated form. Other optical properties of this colloid, likewise, were found to be similar, except that alpha seemed to be slightly higher in the untreated form and the birefringence correspondingly lower. It is concluded that the values given in table 17 for the Ca-saturated materials may be taken as characteristic of the natural substances.

Effects of saturation with various bases. Any single soil colloid may show considerable variation in its indexes of refraction, perhaps partly depending upon the base with which it has been saturated. Our results illustrating this point are given in table 18. The variations are not systematic.

Notable differences in the behavior of the Ca- and Na-saturated soil colloids were observed under the microscope, though the differences were of degree rather than of kind. When mounted in oils, both were seen to be made up of relatively large, coherent grains. But in water mount, the flakes of the Ca-saturated form of Yolo 431, for instance, immediately and suddenly suffered partial disintegration to a mixture of doubly refracting grains 40 to 80 μ in diameter and interstitial minute grains showing Brownian movement. The Na-saturated form of this colloid underwent the same kind of disintegration in water, but much more completely, so that only a few medium-sized flakes remained, with vague boundaries, low birefringence, and hazy extinction, all the rest of the clay fragments having broken down into minute grains showing Brownian movement.

Effect of dispersion. The Na-saturated soil colloid 431 was leached with water, and while still moist was mounted in water for study under the microscope. Only minute grains were to be seen, and when the preparation was made sufficiently dilute, these grains showed Brownian movement. The movement was stopped by the introduction of a little saturated NaCl solution. The progress of the effect was watched as it crossed the microscope slide.

Grains on one side of the field were still dancing, after those on the other side had become quiescent. Then flow of the NaCl solution across the slide caused the grains to collect in small clusters, in which, however, the grains were still perfectly distinct. The individual particles, where shape could be distinguished, did not appear noticeably platy.

A sample of Ca-saturated colloid 431 was digested for 24 hours with 4 *N* NaCl, dispersed in water until no large grains could be seen under the microscope, flocculated by leaching with methyl alcohol, and dried in the laboratory at ordinary temperatures. The Na-saturated product was pulverized and then

TABLE 18

Optical properties of soil colloids saturated with various bases*

SERIES	LABORATORY NUMBER	BASE	DR†	INDEXES OF REFRACTION			$\gamma - \alpha$	EXTINCTION	NOTES
				Alpha	Beta	Gamma			
			per cent						
Yolo	431	Ca	100	1.554	1.569	1.569	0.015	0–18°	Fair flakes
	431	Mg	100−	1.540	1.552	1.554	0.014	0–30	Poor flakes; also higher indexes
	431	K	100	1.558±		1.568±	0.010+	0	Poor flakes
	431	Na	100	1.558		1.570	0.012	0–20	Poor flakes
	7083	Ca	100	1.567	1.586	1.587	0.020	0 usually	Rarely lower n.
	7083	Mg	100	1.567±	1.586	1.586	0.019±	0 approx.	Good plates
	7083	Na	100	1.562	1.580	1.582	0.020	0	Rarely higher n.
Redding	16305	Ca	100−	1.593		1.600	0.007	0	Also lower n.
	16305	Mg	50±	1.591±		1.598±	0.007		
	16305	Na	50±	1.585+		1.590+	0.005	0 approx.	Up to 1.600
Sierra	16308	Ca	100	1.590	1.597	1.600	0.010	0–30	
	16308	Mg	100?	1.592		1.600	0.008		Poor flakes
	16308	Na	100	1.589		1.595	0.006	0 approx.	Poor flakes

* All determinations on thin films after long standing over 52 per cent H_2SO_4.

† DR = Double refraction.

studied in oils under the microscope. The large optical units were found to have formed again and to have the same optical properties as before dispersal. This experiment proves that the large flakes can be dispersed and formed again, apparently at will.

Effect of time of subsidence. The time of subsidence of the original Yolo soil 7083 was varied in order to test the effect upon the formation of large optical units. First, the upper 8 cm. of an aqueous suspension of the original soil was drawn off after only 1 hour of subsidence. The dried natural colloid thus obtained was studied in oils and found to be made up of minute bodies up to 10 μ in diameter, some of which were enveloped in birefringent, yellow

jellylike masses 20 to 50 μ across. In a second test the upper 8 cm. of the suspension was drawn off after standing 48 hours. In this case the jellylike masses were larger on the average (20 to 60μ), better formed, more uniformly birefringent, and much more completely enclosing the numerous inclusions. That is to say, 48 hours of settling somehow promoted the formation of the birefringent, jellylike masses upon evaporation of the suspension. In a third test the original 7083 soil was shaken with water in a cylinder and allowed to stand for about a week. A sample of the upper part of the flocculent layer which had settled in the cylinder was then taken, quickly dried below 100°, and studied in oils. It was found to be made up chiefly of flat flakes of a brown, jellylike substance, full of minute inclusions with high relief. These optical units were 50 to 60 μ in diameter and 10 to 15 μ thick. The flaky character was more noticeable than that in the previous samples.

TABLE 19

Effect of oxalic acid treatment of Ca-saturated clay aggregates

SERIES	LABORATORY NUMBER	GAMMA		$\gamma - \alpha$		COLOR CHANGES AND OTHER NOTES
		Before treatment	After treatment	Before treatment	After treatment	
Vina	16055	1.572	1.562	0.008	0.008	Poor flakes before and after; brown to gray-brown
Keefers	16057	1.60+	1.580	Mostly isotropic		Determinations very difficult
	16058	1.610	1.573	Isotropic	0.000–0.004	Determinations difficult
Sierra	16309	1.604	1.570	0.012	0.014	Rich brown to yellow-brown
Redding	16315*	1.550–1.558	1.559	0.015	0.015	Pale brown to lemon-yellow; good plates before and after
	16319	1.604+	1.573	0.003	0.008	Deep brown to pale brown; poor flakes to good plates
	16321	1.600	1.564	0.008	0.012	Rich brown to pale yellow

* After acid treatment sample 16315 gave a biaxial figure with small 2V; the moisture content of this sample had but little effect on the indexes.

Birefringence of moist colloids. Several soil colloid samples were studied while still somewhat moist. Even in these cases large birefringent units of the order of 0.1 mm. had already formed. Some, but not all, of the birefringent units were, in part, pressure effects, "form double refraction" (2), due to smearing the moist colloid in handling.

Effect of oxalic acid treatment. Seven soil colloids were leached for several days with an aqueous solution of oxalic acid and sodium oxalate. The effect is shown in table 19. It will be noted that, in general, the depth of color and the indexes of refraction were reduced and the birefringence was increased by acid treatment. It is also apparent that those soil colloids with the highest indexes showed the greatest reduction in indexes by acid treatment,

and that after the treatment gamma was not greater than 1.580 or lower than 1.559. In every property, and in almost every case, the colloids were more nearly similar after the acid treatment than before.

RESULTS OF X-RAY STUDY

X-ray diffraction patterns from all the colloid samples described in this paper were obtained by the use of molybdenum radiation rendered virtually monochromatic by filtration through zirconia screens. The powdered materials were packed in thin-walled soft glass tubes having an internal diameter of about 0.6 mm. and were exposed in cylindrical cassettes having a radius of 8 inches, which were especially designed to register lines corresponding to spacing as wide as 20Å.

From measurements of the patterns interplanar spacings corresponding to all clearly recognizable lines were recorded. The results are presented in tables 22 to 37. By comparison with suitable reference data for known substances, it has been possible in most cases to decide definitely which classes of clay minerals are present in the colloids and to draw some limited conclusions regarding other constituents. As has been pointed out by Kelley and Dore (21) in an earlier publication, three types of clay minerals may be recognized singly or in admixture, from their diffraction patterns; namely, the kaolinite-halloysite type, the montmorillonite-beidellite type, and the muscovitelike type (designated as the "x" mineral).

In a recent paper by the authors (25), a series of reference spacings for kaolinite and montmorillonite were tabulated. These spacings are reproduced in table 20, to which are added reference spacings for the identification of the "x" mineral. The theoretical basis for the selection of the kaolinite and montmorillonite reference spacings has been discussed in the former paper and will not be repeated here. The reference spacings for the "x" mineral were derived from the data recently published by Grim, Bray, and Bradley (13).

These investigators have isolated from argillaceous sediments in Illinois, a clay mineral which appears to be similar to, if not identical with, the muscovite-like clay mineral mentioned by Ross and Kerr (35), the mineral designated by Endell, Hofmann, and Maegdefrau (10) as "Glimmerton," and the third type of clay mineral found in California soils. The name "illite" was proposed by them as a group name to designate "the clay mineral constituent of argillaceous sediments belonging to the mica group." Five samples of illite isolated by these investigators showed fairly constant optical properties and closely related chemical composition; however, these workers anticipated that other clay minerals of micaceous origin might be discovered with somewhat different properties, thus requiring new names to describe the variants and some broadening of the significance of the term "illite" as a group name.

The present authors feel that it would be premature to advance the claim that the "x" mineral, found in California soil colloids, properly belongs to the

TABLE 20

Theoretical interplanar spacings for clay minerals

KAOLINITE [GRUNER (14)]			MONTMORILLONITE [MAEGDEFRAU AND HOFMANN (27)] (AT ROOM TEMPERATURE)			ILLITE [GRIM, BRAY AND BRADLEY (13)]		
Spacing d	Intensity	Miller indexes	Spacing d	Intensity	Miller indexes	Spacing d	Intensity	Miller indexes
Å.			Å.			Å.		
			ca. 14–15	v.v.s.	(001)			
7.14	10	(002)				9.98	s.	(002)
			ca. 5	Variable	(003)	4.97	w.	(004)
			4.49	v.s.	(110) (020)	4.47	s.	(110)
4.397	6	(110) (11$\bar{1}$)						
4.248	3	(021)						
						4.11	v.w.	(022)
						3.7	v.w.	(023)
3.570	10	(004)						
						3.40	v.w.	(11$\bar{4}$)
*3.33	Indistinct	(11$\bar{3}$)				*3.31	m.	(006)
			ca. 3.0	Variable	(005)	3.2	v.w.	(114)
						2.98	w.	(025)
						2.84	v.w.	(115)
2.582	5	(114) (11$\bar{5}$)	2.59	s.	(130) (200)	2.56	v.s.	(20$\bar{2}$)
2.48	5	(131) (132)						
						2.44	w.	(13$\bar{3}$)
2.38	2	(006)				2.38	m.	(133)
2.343	8	(132) (13$\bar{3}$)						
2.261	4	(202) (20$\bar{4}$)	2.24	v.w.	(220) (040)	2.24	m.	(22$\bar{1}$)
						2.18	w.	(22$\bar{3}$)
						2.11	w.	(043)
2.015	4	(222) (22$\bar{4}$)						
1.987		(134)				1.98	m.	(0010)
1.826	2	(13$\bar{6}$)						
1.671		(240) (24$\bar{2}$)	1.70	m.	(240) (310) (150)			
1.669	7	(136) (13$\bar{7}$)						
1.665		(151) (152)				1.65	w.	(1310)
						1.64	m.	(312)
1.530	3	(137) (13$\bar{8}$)						
			1.495	s.	(330) (060)	1.50	s.	(060)
1.483	8	(060)						
1.481		(332)						
1.465	2	(33$\bar{3}$)						
						1.34	v.w.	(335)
1.297	4	(1, 3, 10$\bar{}$)	1.30	w.	(260) (400)	1.29	m.	(400)
1.235	3		1.245	w.	(420) (350) (170)	1.24	w.	(0016)

* Quartz (101) spacing = 3.34 v.v.s.

Adjacent spacings bracketed together signify a broad band extending over the indicated range, instead of a sharp line.

Symbols for the intensities of the x-ray reflections: v.s. = very strong; s = strong; m.s. = medium strong; m. = medium; w-m. = weak to medium; w. = weak; v.w. = very weak; v.v.w. = very, very weak; tr. = trace; ? = doubtful.

illite group. So far no attempt has been made to isolate it by methods similar to those employed by Grim and his co-workers; hence it has not been possible to compare either the optical properties or the chemical composition of these materials with that given for illite. The x-ray patterns of the California colloids, however, contain lines which agree well with the lines reported for illite, and this suggests rather strongly that an important constituent of these colloids is a clay mineral belonging to or closely related to this group.

It should be evident from the foregoing discussion that present knowledge does not warrant definite conclusions as to the exact spacings of the "x" mineral found in California soils. Since these colloids may prove to fit into the illite classification, however, it is interesting to compare their interplanar spacings with those which have been established for illite. Again we advance the principle, set forth in our previous paper (25), that only spacings which can be indexed with respect to an established unit cell are acceptable as reference spacings. The list of spacings given by Grim et al. (13) for illite essentially meets this requirement. Although these authors do not give definite lattice dimensions for illite, they have presented a set of interplanar spacings for that mineral in comparison with the spacings calculated for muscovite from the data of Jackson and West (19). As the interplanar distances differ only slightly, Grim et al. concluded that the illite crystal cell is almost like the muscovite cell, differing from it by being only about one-third per cent shorter in the direction of the c axis. The numerical differences between the values for the interplanar spacings for muscovite and illite are so slight that the spacings for each may be assigned the same indexes with but little likelihood of error. The lines of the illite structure appear to be the most satisfactory set of reference lines now available for comparison with the "x" mineral of California soil colloid.

The lines in the patterns of many soil colloids are more or less diffuse because of the presence of considerable very finely divided material, which tends to produce broadened lines, or because of the presence of noncrystalline material, which tends to produce undue darkening of the background. In addition, as seen from the tables, nearby lines tend to overlap, even in the pattern of only a single mineral; when two or three different clay minerals are present, the overlapping may be much greater. Accordingly, an attempt to identify all of the lines in a soil colloid pattern is attended with many uncertainties.

Fortunately, it is usually possible to identify the clay minerals by the wide spacings, disregarding entirely the rest of the pattern. Thus with air-dried material the 14–15Å. spacing is characteristic of the montmorillonitic group of clays; the 10Å. spacing, of the "x" mineral; and the 7Å. spacing, of the kaolinitic group. The exact numerical values of these spacings, as ordinarily determined, vary slightly, partly because of lack of refinement in technic and perhaps partly because each of the three clay mineral types may be represented by several individual minerals having slightly different lattice constants. The variation among these values is not wide, however, and in no case is it likely to lead to erroneous identification.

The identification, made on the basis of the wide spacings, may be confirmed by examining the same materials after heating to 500° for some hours. In the pattern of the heated materials, the characteristic montmorillonite line is in a new position corresponding to a spacing of about 9.5–10Å.; the 7Å. line, characteristic of unheated kaolinite, is entirely absent; and the 10Å. line, characteristic of the "x" mineral, remains unchanged.

As has been indicated in this paper under the discussion of optical properties, when soil colloids are separated by decantation, the clay particles tend to form aggregates and to entangle mineral fragments of varying sizes. Correspondingly, the x-ray diffraction patterns of nearly all the colloids that we have examined give evidence of the presence of minerals other than the three clay types. Outstanding among these is quartz, which is almost invariably present.

TABLE 21

Theoretical interplanar spacings for important mineral inclusions

ALPHA QUARTZ			ZIRCON			RUTILE		
Spacing	Intensity	Miller indexes	Spacing	Intensity	Miller indexes	Spacing	Intensity	Miller indexes
Å.			Å.			Å.		
			4.65	m.s.	(110)			
			4.40		(101)			
4.25	m.	(100)						
			3.66	v.s.	(111)			
3.34	v.v.s.	(101)						
			3.29		(220)			
						3.24	v.s.	(110)
2.45	m.	(110)	2.50	s.	(112)	2.48	s.	(101)
2.28	m.	(102)	2.33	w.	(220)	2.29	w.	(200)
1.81	m.s.	(112)						
1.80		(003)						
			1.74	v.s.	(231)			
1.67	m.	(202)				1.68	v.s.	(121)
1.54	s.	(121)				1.62	s.	(220)
1.38	v.s.	(122)	1.41	s.	(114)	1.42	w.	(221)

Optical evidence has been noted for the occurrence of zircon, rutile, and iron oxide. As will be shown later, the x-ray data confirm the optical evidence. Quartz, zircon, and rutile give characteristic x-ray patterns, and, even in complex mixtures, it is sometimes possible to recognize lines produced by spacings in these minerals.

Two forms of quartz have been recognized by crystallographers, and crystal structures have been assigned to each. The alpha form is stable at temperatures below 573°, and the beta form exists at temperatures between 573° and 870°. According to Bragg (4, p. 84) the alpha-beta transformation of quartz takes place rapidly and is reversible. According to Dana and Ford (9, p. 471), alpha quartz occurs in geodes and veins, whereas the beta modification was the original form in granites and porphyries.

In table 21 are given the interplanar spacings for the strongest x-ray re-

TABLE 22

Interplanar spacings of the Yolo colloids

MINERALS*	431		7083		17557		17558		17559	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.
M	15.4 s.	10.1 m.s.	15.3 s.	10.1 w.	15.2 s.	10.0 w–m.	15.4 s.	10.0 w.	15.3 s.	10.1 w.
K					7.3 m.		7.3 v.w.		7.3 v.w.	
M	4.49 s.	4.5 s.	4.5 s.	4.5 s.	4.5 s.	4.5 s.	4.5 s.	4.45 m.s.	4.5 s.	4.5 s.
Q	3.35 w–m.	3.35 m.	3.36 s.	3.4 w.	3.33 s.	3.35 s.	3.32 s.	3.35 s.	3.32 m.	3.35 s.
M	3.15 w–m.	3.20 w–m.			3.2 v.w.		3.18 v.w.	3.20 w.	3.23 w.	3.20 w.
MK	2.60 s.	2.60 w.	2.57 s.	2.63 m.	2.57 s.	2.62 m.	2.59 s.	2.60 m.s.	2.57 m.s.	2.62 s.
	2.56	2.52		2.50			2.52			2.56
Q	2.45 w.	2.42 v.w.		2.45 w.	2.43 m.	2.45	2.41 w.	2.45 m.s.		2.45 w.
MK				2.25 w–m.				2.30 s.		2.27 w.
U	2.13 w.		2.13 w.					2.16 m.		
KQ			1.83 w.		1.82 w.	1.82 w.	1.82 w.	1.83 s.		1.82 w.
MQ	1.70 m.	1.70 w.	1.70 w.	1.70 v.w.	1.71 w.	1.70 w.	1.72 w.	1.68 m.	1.69 v.w.	1.70 w.
K	1.64	1.66	1.66		1.64	1.66	1.65			1.68
KQ	1.53 v.w.	1.53 w–m.		1.53 m.	1.54 w.	1.54 m.s.	1.53 m.	1.55 s.	1.53 w.	1.54 s.
M	1.50 m.	1.50	1.50 m.s.	1.50	1.50 m.s.	1.50	1.49 s.	1.52 w.	1.49 s.	1.50
Q						1.37 w–m.		1.39 s.		1.38 s.
MK	1.29 v.w.	1.29 v.w.	1.29 w.	1.30 w.	1.295 w.	1.30 w.	1.29 w.	1.30 v.w.	1.29 w.	1.30 w.
MK						1.25 w.		1.26 w–m.		1.25 w.

* *Symbols for minerals:* I = "i" mineral; K = kaolinite; M = montmorillonite; Q = quartz; R = rutile; Z = zircon; U = unidentified mineral. These letters signify that the particular line in the pattern might be due to the indicated mineral, not that the presence of the mineral is necessarily established by the line.

flections of alpha quartz and of zircon and rutile. The numerical values for these spacings have been calculated from the unit cell dimensions for these minerals, as recorded by Bragg (4). The visual intensities of the reflections, as given in the table, were observed by the present authors on diffraction patterns made from authentic samples of the respective minerals. Account is taken of only a few of the strongest lines for each mineral, since only these are of value for identification in mixtures.

In the following sections are given the findings for the different series of colloids discussed in this paper. In general, the clay minerals were identified by the data presented in the odd-numbered tables, which give only the wide

TABLE 23

Effect of partial dehydration on interplanar spacings of Yolo colloids

SAMPLE NUMBER	TEMPERATURE	MONTMORILLONITE SPACINGS	KAOLINITE SPACINGS
	°C.	Å.	Å.
431	25	15.4	None
	100	15.2	None
	300	10.7	None
	500	10.1	None
7083	25	15.3	None
	100	14.5	None
	300	10.3	None
	500	10.1	None
17557	25	15.3	7.3
	500	10.0	None
17558	25	15.4	7.3 v.w.
	100	14.5	7.3 v.w.
	300	11.6	7.3 v.w.
	500	10.0	None
17559	25	15.3	7.3
	500	10.1	None

Note: No "x" mineral spacings found in any of these samples.

spacings and the effect upon them of partial dehydration. Confirmation was then sought from the complete list of spacings found in the even-numbered tables, and these lists were then scrutinized for evidence of quartz and other inclusions.

Yolo clay colloids. The data in tables 22 and 23 show that the Yolo samples are preponderantly montmorillonitic. All the 25° samples showed a strong spacing of 15.2 to 15.4Å., whereas the samples heated to 500° showed a 10Å. spacing. Furthermore, the samples heated to 100° and 300°, respectively, showed spacings intermediate between the 15 and 10Å. values. These spacings all correspond to the characteristic spacing in montmorillonite, designated

by Hofmann, Endel, and Wilm (18) as the (001) spacing, which varies according to heat treatments. In the Davis colloids (samples 17557–17559), the presence of a 7.3Å. spacing in the 25° samples and its absence in the samples that were heated to 500°, affords definite evidence of kaolinite or related minerals. Neither the La Habra (sample 431) nor the Gilroy (sample 7083) Yolo clay colloid gave a 7Å. spacing, from which it may be concluded that kaolinitic material is not present in significant quantity in these colloids. None of the unheated Yolo colloids gave a 10Å. spacing; hence no important quantity of the "x" material was present.

TABLE 24

Interplanar spacings of the Vina colloids

MINERALS*	16054		16055		16056	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å		Å.	Å.	Å.	Å.
M		No pattern	ca. 15 ?		15.4 v.w.	
K	7.3 m.	No pattern	7.3 m.	7.3 w.	7.24 m.	ca. 7 v.v.w.
U	5.95 v.v.w.	No pattern	5.9 w.			
U	5.4 ?	No pattern	5.4 w.			
MKI	4.5 s.	No pattern	4.45 s.	4.5 m.	4.45 s.	4.45 s.
U		No pattern			4.05 v.w.	4.05 w.
K	3.6	No pattern	3.6 m.		3.6 w.	
Q	3.3	No pattern	3.32 w–m.	3.35 w.		
M		No pattern			3.18 w.	3.21 w.
K	2.57 m.	No pattern	2.58 s.	2.57 w.	2.60 m.s.	
K		No pattern			2.50	2.51 w.
K		No pattern	2.35 w.		2.32	
K		No pattern	2.20 w.			
Q	1.69 m.	No pattern	1.69 m.	1.68 v.w.	1.69 m.	1.69 m.
MK	1.50 m.	No pattern	1.50 s.		1.50 s.	1.50 w.
K	1.275 v.w.	No pattern	1.29 v.w.		1.295 v.w.	
K		No pattern	1.24 v.w.		1.24 v.w.	

* See footnote table 22.

Quartz was present in all of the Yolo samples, as shown by the distinct 3.32–3.36Å. spacing, which represents the strongest reflection of quartz. Supplementary evidence is furnished by the 2.45, 1.82, 1.54, and 1.38 spacings found in most of the patterns.

Vina clay colloids. The Vina clays were, in general, rather less crystalline than the other colloids that have been examined. The patterns obtained from this series showed considerable general darkening of the background, and the diffraction lines were, in some instances, difficult to distinguish. All three samples show definitely the presence of the 7Å. spacing in the unheated materials (table 24). In one instance this spacing disappeared on heating to 500°; in the other two, the intensity of its reflection was much diminished

(table 25). These observations indicate the presence of kaolinitic material as the predominating clay mineral. Two of the samples showed the presence of a weak 15Å. line in the unheated form. This suggests that a small amount of montmorillonitic material was probably also present. No evidence for the presence of the "x" mineral was found. Quartz was present in small amounts.

In view of the small number of Vina samples that have been studied and of their poorly crystalline character, the conclusions from the x-ray data should be accepted with some reserve.

Keefers clay colloids. The tabulation of wide spacings given in table 27 shows that the only clay mineral present in recognizable quantity was of the kaolinitic type. The complete list of spacings in table 26 supports this finding, in that the patterns obtained from the heated materials show only a few spacings remaining after the thermal destruction of the kaolinite crystal

TABLE 25

Effect of partial dehydration on interplanar spacings of Vina colloids

SAMPLE NUMBER	TEMPERATURE	MONTMORILLONITE SPACINGS	KAOLINITE SPACINGS
	°C.	Å.	Å.
16054	25	None	7.3
	100	None	7.3
	300	None	7.3
	500	None	None
16055	25	ca. 15 ?	7.3
	100	13.8 ?	7.3
	300	None	7.3
	500	None	7.3 w.
16056	25	15.4 v.w.	7.25
	500	None	ca. 7 v.v.w.

Note: No "x" mineral spacings found in any of these samples.

structure. These remaining spacings, of rather weak intensity, are not related to the patterns of the clay minerals; they are rather to be ascribed to quartz and possibly to zircon and other mineral inclusions, thus supporting the optical evidence for the presence of these minerals.

Sierra clay colloids. The data in table 29 show that all four horizons of the Mount Orcum profile gave patterns containing the strong 7Å. kaolinite line, which disappeared when the samples were heated to 500°. This establishes the essentially kaolinitic nature of these colloids. In addition, all the samples showed the presence of a weak 10Å. line. The presence of this line was certain, however, only in material which had been heated to 500°, and, from the wide spacing data of table 29, this spacing could be due to either montmorillonite or the "x" mineral. Confirmatory evidence for the presence of montmorillonite would be a stronger 15Å. spacing in the unheated material. Sam-

ple 16309 showed a feeble indication of a montmorillonite spacing when heated to 100°C. and a doubtful indication of the "x" mineral in the unheated

TABLE 26

Interplanar spacings of the Keefers colloids

MINERALS*	16057		16058	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å	Å.	Å.	Å.
K	7.25 m.s.		7.25 m.	
Z		4.60 w.		
K	4.40 m.s.		4.40 s.	4.45 m.
K	4.25 v.w.			
Z		3.80 ?		
K	3.52 m.		3.55 m.	
Z		3.40 w.		
Q	3.32 m.		3.33 w–m.	3.33 m.
K	2.58 m.		2.57	
Z		2.53 m.		2.51 w.
K	2.50		2.48	
K	2.34 w.		2.35 w–m.	
U	2.20 v.w.	2.20 v.w.	2.20 w.	
K	1.97 v.w.			
KQR	1.70 w.	1.69 w.	1.69 m.	1.70 w.
K	1.66			
Q	1.535 v.w.	1.55 v.w.		
U	1.49 m.s.	1.46	1.49 s.	
Q	1.37 v.v.w.			
K	1.29 v.v.w.		1.295 v.v.w.	
K	1.24 v.v.w.		1.23 v.v.w.	

* See footnote table 22.

TABLE 27

Effect of partial dehydration on interplanar spacings of Keefers colloids

SAMPLE NUMBER	TEMPERATURE	KAOLINITE SPACINGS
	°C.	Å.
16057	25	7.25
	100	7.3
	300	7.3
	500	None
16058	25	7.25
	500	None

Note: No montmorillonite or "x" mineral spacings found in any of these samples.

material. In the other three samples of this profile confirmatory evidence of montmorillonitic material is entirely lacking. Accordingly a decision as to

TABLE 28

Interplanar spacings of the Sierra colloids

TABLE 28

Interplanar spacings of the Sierra colloids

MINERALS*	16308		16309		16310		16311	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.
I		10.3 w.	10.1 ?	10.1 w.		10.1 w.		10.1 v.w.
K	7.25 m.s.		7.30 m.s.		7.3 m.s.		7.25 s.	
U			5.90 w.					
IZ		4.55 s.		4.5 s.				4.5 v.w.
IZ			4.45 s.		4.5 s.	4.45 m.	4.45 v.s.	
KZ	3.59 s.		3.62 m.s.				3.60 s.	
Q	3.33 w.	3.33 w.		3.32 w–m.		3.35 w.	3.35 w.	3.35 v.w.
U						2.71 w.	2.72 tr.	2.70 v.w.
KI	2.62 m.	2.60 w.	2.60 w.	2.62 v.w.			2.60 m.	
KIZ	2.52 m.	2.52 w.	2.50 w.	2.53 v.w.	2.50 m.		2.50	2.50 v.w.
R						2.48 w.		
IQ		2.43 w.		2.42 v.w.				
KI	2.39 w.				2.37 w.			
K	2.32 w–m.		2.34 w.				2.35 w–m.	
Q		2.27 v.w.						
I	2.17 v.w.	2.17 v.w.	2.17 v.w.	2.17 w.	2.16 v.w.	2.20 w.	2.18 w.	2.20 v.w.
KI	1.98 w.	1.98 v.w.	1.99 w.					
U		1.89 v.w.				1.90 v.w.		
Q		1.83 v.v.w.		1.83 w.		1.83 w.		1.83 w.
KQR	1.69 m.s.	1.68 v.v.w.	1.68 w–m.	1.68 w.	1.68 m.	1.68 w–m.	1.72 m.	1.69 w–m.
	1.66						1.66 m.	
KQ	1.53 m.s.	1.53 w.	1.53 w.	1.53 w.	1.53 v.w.	1.53 v.w.	1.53 w.	1.53 w.
KI	1.485 s.		1.50 m.	1.50 w.	1.50 m.	1.49 v.w.	1.50 s.	1.50 w.
U							1.47 v.w.	1.45 w.
KI	1.285 v.w.					1.29 v.w.	1.29 v.w.	1.29 v.w.
KI	1.235 v.w.					1.24 v.w.	1.24 w.	1.24 v.w.

* See footnote table 22.

the clay minerals present, other than kaolinite, cannot be made on the basis of the wide spacing tabulated in table 29.

The complete tabulation of all spacings, as given in table 28, affords more convincing evidence, especially the spacing obtained from the material heated to 500°. After the destruction of the kaolinite structure by heating, the remaining simplified pattern contains several lines which correspond with the reference spacing of the "x" mineral rather than with those of montmorillonite. Other spacings characteristic of quartz, zircon, and rutile, as well as unidentified spacings, are found in the patterns from the 500° samples. These results are consistent with the optical observations on the Sierra clays.

Redding clay colloids. A spacing of about 7Å. was found in all thirteen of the air-dried Redding samples (tables 30a, 30b, 30c) but was absent from the samples when heated to 500°. This establishes the presence of kaolinite or

TABLE 29

Effect of partial dehydration on interplanar spacings of Sierra colloids

SAMPLE NUMBER	TEMPERATURE	MONTMORILLONITE SPACINGS	KAOLINITE SPACINGS	"x" MINERAL SPACINGS
	°C.	Å.	Å.	
16308	25	None	7.25	None
	500	None	None	10.3
16309	25	None	7.3	10.1 ?
	100	14.8 (v.w.)	7.3	None
	300	None	7.3	None
	500	None	None	10.1
16310	25	None	7.3	None
	500	None	None	10.1
16311	25	None	7.25	None
	500	None	None	10.1

related minerals in all of the Redding colloids. The 15Å. spacing, characteristic of montmorillonite, was observed in five of the thirteen samples, but in only two of them was the corresponding spacing of about 9.5–10Å. found after the samples were heated to 500°. In only two instances was a strong montmorillonite line observed in the Redding clays, namely, samples 16315 and 16316 from Palermo. The 10Å. spacing, characteristic of the "x" clay mineral, was not observed in any of the Redding clays.

The x-ray data indicate, therefore, that the Redding clays are preponderantly kaolinitic but that certain samples also contain significant amounts of montmorillonite or similar minerals (table 31). The Oroville clays (samples 16317 and 16318) and all except one horizon of the Kearney Mesa and one horizon of the Olinda samples appear to be virtually free from montmorillonitic material. The clay from all three horizons of the Palermo

TABLE 30a

TABLE 30a

Interplanar spacings of the Redding colloids—Kearney Mesa

MINERALS*	16303		16304		16305		16306		16307	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.
M							15.2 w.			
K	7.25 m.		7.4 m.		7.4 w–m.		7.3 s.		7.3 w.	
KM	4.45 m.	4.50 s.	4.4 s.	4.5 v.s.	4.45 m.s.	4.45 m.	4.45 v.s.	4.5 s.	4.45 m.s.	4.5 m.s.
K	3.55 m.		3.53 m.		3.52 m.		3.60 s.		3.60 m.	
Q	3.33 m.	3.37 s.	3.32 m.	3.37 s.	3.33 m.	3.35 m.s.	3.35 m.	3.35 s.	3.35 w–m.	3.35 s.
U					2.72 w.	2.72 w–m.		2.72 w–m.		
KM	2.60 w–m.	2.56 w.	2.60 m.	2.60 m.	2.60 m.		2.60 m.s.	2.60 w.	2.60 m.	2.60 m.
Q	2.52	2.50	2.52	2.50	2.52	2.52 w–m.	2.50	2.50	2.52	2.52
K	2.37 w.		2.36 w.				2.38 m.s.	2.32 w.		
U					2.19 v.w.		2.22 v.w.			
K	1.99 v.w.		1.98 v.w.		1.96 v.v.w.					
KQ	1.83 v.w.	1.83 w.	1.83 v.w.	1.83 w.	1.83 v.w.	1.84 v.w.		1.86 w.		
KQ	1.69 m.	1.69 w.	1.70 w.	1.70 w.	1.70 w–m.	1.69 v.w.	1.71 s.	1.70 w.	1.68 w.	1.68 w.
			1.66	1.67	1.66		1.67			
Q				1.52 w.						
KQ	1.49 s.		1.495 s.	1.50	1.49 m.s.		1.50 v.s.	1.50 w.	1.49 w.	1.49 w.
Q							1.45 w.	1.45 w.		
Q	1.38 v.w.		1.38 v.w.	1.37 w.			1.39 w.		1.37 v.w.	1.37 v.w.
K	1.29 v.w.		1.29 v.w.	1.29 v.w.	1.29 v.w.		1.29 m.			
K	1.24 v.w.		1.24 v.w.	1.25 v.w.	1.24 v.w.		1.24 m.			

* See footnote table 22.

TABLE 30b

Interplanar spacings of the Redding colloids—Sacramento Valley

MINERALS*	PALERMO						OROVILLE			
	16314		16315		16316		16317		16318	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.
M	15.2 ?		15.2 s.	9.6 v.w.	15.0 s.	9.8 w.				
K	7.4 m.		7.4 m.s.		7.4 m.		7.8 w.		7.25 w.	
U	5.8 w.									
KM	4.45 s.	4.45 w.	4.5 w.	4.45 s.	4.45 v.s.	4.45 s.	4.40 s.	4.45 s.	4.45 s.	4.50 s.
Q	4.1 w.						4.20 w.		4.25 w.	
U								3.75 w.		
K	3.58 m.s.		3.55 m.		3.58 m.s.		3.57 w.		3.50 w.	
Q	3.32 s.	3.33 w.		3.35 v.w.		3.30 w.	3.32 s.	3.35 v.s.	3.33 s.	3.35 v.s.
U	2.68 m.						2.67 w.	2.70 m.s.		2.70 m.
KM	2.60 m.		2.60 s.	2.60 m.s.	2.60 v.s.	2.60 m.	2.60 m.		2.60 w–m.	
Q	2.50	2.51 w.	2.52	2.50	2.50	2.50	2.50		2.50	2.53 s.
K	2.36 m.		2.35 m.		2.37 m.		2.32 w.		2.35 w.	
U							2.21 v.w.	2.23 s.		2.22 w–m.
K	1.98 v.w.						1.97 v.w.			
U	1.92 v.v.w.						1.91 v.w.			
K	1.83 v.w.						1.82 v.w.	1.83 m.s.	1.82 v.w.	1.83 m.
KM	1.71 w.	1.69 v.w.	1.69 w.	ca. 1.70 v.w.	1.71 m.	1.68 w.	1.68 w.	1.69 s.	1.68 w–m.	1.70 m.s.
	1.66				1.67					
KQ							1.54 w.			1.52 s.
KM	1.49 s.		1.50 v.s.	ca. 1.50 w.	1.50 v.s.	1.50 m.s.	1.50 s.	1.49 w.	1.49 s.	
K	1.46 v.w.						1.45 m.	1.45 w–m.	1.46 v.w.	1.46 v.w.
Q	1.38 w.						1.37 w.m.	1.38 m.	1.37 v.v.w.	1.38 v.w.
K	1.29 v.w.		1.29 w.		1.29 m.		1.29 v.w.	1.31 v.w.	1.29 v.v.w.	
K	1.24 v.w.		1.24 v.w.		1.24 m.		1.24 v.w.	1.26 v.w.	1.235 v.v.w.	1.26 v.w.

* See footnote table 22.

profile (samples 16314–16316) gave x-ray indications of the presence of montmorillonite which were especially strong in the 20–40-inch horizon (sample 16315). This is an interesting confirmation of the chemical and optical data reported above.

TABLE 30c

Interplanar spacings of the Redding colloids—Olinda

MINERALS*	16319		16320		16321	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.
M	15.0 w.					
K	7.3 s.		7.25 s.		7.25	
KM	4.5 s.	4.5 s.	4.40 v.s.	4.50 s.	4.40 v.s.	4.45 s.
K	4.25 w.		4.20 w.		4.25 v.w.	
U				3.70 v.w.		
K	3.58 m.s.		3.57 m.		3.58 m.	
Q	3.35 m.s.	3.35 s.	3.31 m.	3.35 s.	3.32 w.	3.32 s.
U	2.70 w.	2.70 s.	2.70 w.	2.70 s.	2.70 w.	2.70 m.s.
K	2.62 s.		2.60 m.s.		2.60 m.s.	
U	2.52	2.52 s.		2.52 v.s.		2.52 s.
K			2.50		2.50	
K	2.37 m.		2.37 m.		2.37 m.	
U	2.22 w.		2.20 w.	2.20 w–m.	2.21 w.	2.21 w–m.
K	2.00 w.		1.98 v.w.		1.98 v.w.	
U						1.87 v.w.
KQ	1.85 w.	1.82 w.	1.83 v.w.	1.83 m.	1.83 v.w.	1.82 w.
KQ	1.72 w.		1.70 m.s.	1.70 m.s.		1.70 s.
KQ	1.68	1.68 m.s.	1.66			
U		1.58 w.				
K	1.53 w.		1.54 v.w.			
K	1.50 v.s.		1.49 s.	1.49 m.		1.50 w–m.
K	1.47 w.		1.46 w.			
Q		1.43 w.m		1.45 m.		1.45 w–m.
Q	1.39 w.	1.38 v.w.	1.38 v.w.	1.38 w.		1.38 w.
K	1.29 v.w.		1.29 v.w.	1.29 v.w.		1.29 v.w.
K	1.24 w.	1.24 v.w.	1.24 v.w.	1.24 v.w.		1.24 v.w.

* See footnote table 22.

Most of the Redding samples gave evidence of quartz. Unidentified spacings point to the presence of other inclusions but furnish no clue to their identity.

San Joaquin clay colloids. All the x-ray diffraction patterns obtained from the samples of the San Joaquin soils showed the 10Å. spacing characteristic of the "x" mineral, and all patterns also showed the 7Å. spacing of kaolinite, which disappeared in every case except one upon heating to 500°C. (table 33). The disappearance of this spacing on heating definitely confirms the presence

TABLE 31

Effect of partial dehydration on interplanar spacings of Redding colloids

SAMPLE NUMBER	TEMPERATURE	MONTMORILLONITE SPACINGS	KAOLINITE SPACINGS
	°C.	Å.	Å.
16303	25	None	7.25
	500	None	None
16304	25	None	7.4
	100	None	7.4
	300	None	7.4
	500	None	None
16305	25	None	7.4
	500	None	None
16306	25	15.2	7.3
	500	None	None
16307	25	None	7.3
	500	None	None
16314	25	15.2	7.4
	500	None	None
16315	25	15.2	7.4
	500	9.6	None
16316	25	15.0	7.4
	500	9.8	None
16317	25	None	7.3
	500	None	None
16318	25	None	7.25
	500	None	None
16319	25	15.0	7.3
	500	None	None
16320	25	None	7.25
	500	None	None
16321	25	None	7.25
	500	None	None

Note: No "x" mineral spacings found in any of these samples.

of kaolinitic material, the single exception of a weak reflection being ascribed to incomplete heat treatment. The 15Å. line characteristic of montmorillonite was not found in any pattern of the San Joaquin colloids. The

data, therefore, definitely establish that the clay minerals of the San Joaquin soils are of the kaolinitic and the "x" mineral types, and that the montmorillonitic type is absent.

The more detailed data of tables 32a and 32b indicate that most of the spacings in the patterns of the San Joaquin clays may be identified with kaolinite and the "x" mineral. Quartz spacings were also present in all of the patterns.

TABLE 32a

Interplanar spacings of the San Joaquin colloids—Fairmead and Pixley Area

MINERALS*	6530		18882		18883	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.
I	10.0 m.	10.0 m.	10.1 w.	10.1 w.	10.1 w.	10.1 w.
K	7.25 w.		7.3 m.	7.3 w.	7.4 w.	
KI	4.42 s.	4.5 m.	4.45 m.	4.50 s.	4.45 s.	4.5 s.
Q					4.25 w.	
K					3.57 w.	
Q	3.32 s.	3.35 s.	3.35 m.	3.35 s.	3.33 s.	3.35 v.s.
I		2.95 w.				
KI	2.59 s.	2.62 m.	2.60 m.	2.60 s.	2.60 m.	2.60 v.s.
I					2.54	2.52 w–m.
I	2.42 w.	2.44 m.	2.42 w.	2.45 m.	2.42 w.	2.44 m.
KI			2.27 w.			2.25 w–m.
I	2.17 w.	2.17 m.	2.17 w.	2.17 w.	2.18 w.	2.17
KI	1.98 w.		2.00 v.w.	2.00 w.	2.00 v.w.	1.98 w–m.
KQ				1.82 w.	1.82 v.w.	1.82 w.
KQ	1.69 m.	1.68 w.	1.68 w.	1.70 m.	1.68 w.	1.70 m.
KI	1.66			1.66		1.66
Q	1.53 m.	1.53 s.	1.53 w.	1.53 m.s.	1.54 m.	1.53 s.
I	1.50 m.			1.50 m.s.	1.50 m.	1.50
Q	1.36 w.			1.37 w.	1.37 w.	1.37 v.w.
KI	1.30			1.30 v.w.	1.29 w.	1.29 v.w.
KI					1.24 v.w.	1.24 v.w.

* See footnote table 22.

A few spacings were not identified. No evidence was found for the presence of either zircon or rutile.

Hanford clay colloids. All patterns obtained from the Hanford samples showed the 10.0Å. spacing, indicating that the predponderant clay mineral was the "x" mineral (tables 34 and 35). The presence in the Van Nuys sample (No. 7095) of a small proportion of montmorillonite was indicated by a faint reflection of the 15Å. spacing in the air-dried material. The correspond-

TABLE 32b

Interplanar spacings of the San Joaquin colloids—Terra Bella and Lindcove

MINERALS*	18884		18885		18888		18889	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.
I	10.0 w–m.	10.0 w–m.	10.0 w–m.	10.0 s.	10.2 w.	10.1 w.	10.0 w.	10.0 m.
K	7.25 w–m.		7.25 w–m.		7.25 w.		7.25 m.	
KI	4.50 s.	4.5 m.s.	4.45 v.s.	4.45 s.	4.50 m.	4.50 m.s.	4.45 v.s.	4.50 s.
K	4.40 w.							
K							3.57 s.	
Q	3.35 v.s.	3.35 s.	3.35 s.	3.35 v.s.	3.35 m.s.	3.35 v.s.	3.35 v.s.	3.35 v.s.
I			3.20 w.					
I							2.95 w–m.	
U								2.66 m.s.
KI	2.63 s.	2.62 m.	2.58 v.s.	2.63 m.s.	2.63 m.	2.60 m.	2.57 s.	2.53 m.
I	2.58	2.50		2.50 w.		2.52 w.		2.50 w.
I	2.46 m.	2.43 m.	2.43 m.	2.43 m.	2.43 w–m.	2.43 m.		
U								2.39 w.
Q				2.25 w.		2.29 w.		2.30 v.w.
I	2.17 w–m.		2.18 w.	2.17 w.	2.17 w.	2.17 w–m.	2.17 m.	2.22
KI	2.00 w.		2.00 m.	1.98 w.	2.00 w.	1.99 w.	1.99 w–m.	
U					1.90 v.w.		1.87 w.	1.90 v.w.
Q	1.83 w.	1.83 m.	1.82 w.	1.82 w–m.	1.83 v.w.	1.82 w.	1.82 w.	1.83 v.w.
KQ	1.72 m.s.		1.70 s.	1.68 m.s.	1.68 w.	1.68 m.	1.70 s.	1.68 v.w.
KI	1.66	1.67 m.	1.66				1.64	
Q	1.54 m.s.	1.54 s.	1.53 m.s.	1.53 s.	1.54 s.	1.54 m.s.	1.54 m.s.	1.54 m.s.
I	1.50 s.		1.50 s.	1.47 ?	1.50 s.		1.48 v.s.	
Q	1.39 m.	1.385 m.	1.37 m.	1.38 m.	1.37 w.	1.37 v.w.	1.38 w.	
KI	1.29 v.w.		1.29 v.w.	1.32 v.w.		1.32 v.w.		
KI	1.24 v.w.		1.24 v.v.w.	1.26 v.w.		1.26 v.w.		

* See footnote table 22.

ing 9.5Å. spacing could not be recognized in the material heated to 500°; this is not surprising, as the reflection from the heated material is usually much more diffuse than that from the unheated material. Moreover, this line would be difficult to observe because of its proximity to the 10Å. spacing of the "x" mineral. The "x" mineral was apparently the only clay mineral in the Delano sample (No. 18886). A 7.25Å. spacing in the patterns from the lower temperature Exeter samples (No. 18887), but absent from the 500°

TABLE 33

Effect of partial dehydration on interplanar spacings of San Joaquin colloids

SAMPLE NUMBER	TEMPERATURE	KAOLINITE SPACINGS	"X" MINERAL SPACINGS
	°C.	Å.	Å.
6530	25	7.25	10.1
	100	7.3	10.2
	300	7.3	10.1
	500	None	10.1
18882	25	7.3	10.3
	100	7.3	10.1
	300	7.3	10.3
	500	7.3 w.	10.0
18883	25	7.4	10.1
	500	None	10.1
18884	25	7.25	10.0
	500	None	10.0
18885	25	7.25	10.0
	500	None	10.0
18888	25	7.25	10.2
	500	None	10.1
18889	25	7.25	10.0
	500	None	10.0

Note: No montmorillonite spacings found in any of these samples.

sample, definitely identifies a kaolinitic mineral in addition to the "x" mineral. No montmorillonite spacing was found in this sample.

The complete list of spacings in table 34 shows the presence of quartz in all of the Hanford samples. The probable presence of other mineral inclusions was indicated by several spacings not identified with any known minerals.

Various clay colloids. Inasmuch as the Madera, Tujunga, Ramona, Placentia, and Maxwell soils were represented by a single sample each, and the Tule soil by a single profile, it is not desirable to draw broad conclusions from the x-ray data. Even the tabulation showing the effect of dehydration on

TABLE 34

Interplanar spacings of the Hanford colloids

MINERALS*	7095		18886		18887	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.
M	15.5 w.					
I	10.0 v.w.?	10.0 m.	10.2 w.	10.1 m.	10.0 v.w.	10.1 m.
K					7.25 w.	
U			5.7 w.			
U			5.2 w.			
I	4.5 s.	4.5 m.s.	4.5 s.	4.45 s.	4.45 v.s.	4.5 s.
Q	3.33 m.	3.32 s.	3.35 s.	3.35 s.	3.35 s.	3.32 v.s.
I	3.20 m.	3.18 s.				
U					2.92 v.w.	
U	2.62 m.	2.60 s.	2.62 s.	2.60 m.	2.60 s.	2.61 w–m.
I	2.54			2.50 m.	2.56	
Q		2.45 w.				
I	2.42 m.	2.42	2.44 m.			2.43 w.
I					2.27 w.	2.27 v.w.
I	2.17 w.		2.17 w.	2.20 w.	2.17 w.	2.17 w.
I	1.99 v.w.		2.00 w.	2.00 m.	1.99 w.	1.99 v.w.
U					1.92 w.	1.89 v.w.
Q				1.83 w.	1.83 v.w.	1.82 v.w.
Q	1.70 w.	1.70 v.w.	1.68 m.	1.68 w.	1.72 w.	
I	1.66				1.67	1.67 m.
U				1.60 w–m.	.....	.....
Q	1.53 m.s.	1.53 v.w.	1.53 w.	.....	1.53 m.	1.53 m.s.
I	1.50 m.s.		1.50 s.	1.50	1.50 m.s.	
Q			1.38 w.	1.37 v.w.	1.37 w.	
KI			1.29 v.w.	1.29 v.w	1.29 w–m.	

* See footnote table 22.

TABLE 35

Effect of partial dehydration on interplanar spacings of Hanford colloids

SAMPLE NUMBER	TEMPERATURE	MONTMORILLONITE SPACINGS	KAOLINITE SPACINGS	"X" MINERAL SPACINGS
	°C.	Å.	Å.	Å.
7095	25	15.5	None	10.0
	500	....	None	10.0
18886	25	None	None	10.1
	100	None	None	10.0
	300	None	None	10.1
	500	None	None	10.0
18887	25	None	7.25	10.0
	100	None	7.25	10.1
	300	None	7.25	10.1
	500	None	None	10.1

TABLE 36a

Interplanar spacings of Madera, Tujunga, and Tule colloids

TABLE 36a

Interplanar spacings of Madera, Tujunga, and Tule colloids

MINERALS*	MADERA 6528		TUJUNGA 7094		TULE			
					18890		18891	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.	Å.	Å.
M	15.0 w–m.		15.5 s.				15.0 m.s.	
IM	10.2 tr.	10.0 m.s.		9.7 w–m.	10.0 w.	10.0 w.		9.9 m.
K	7.3 m.		7.0 v.w.		7.25 m.s.		7.3 m.	
MI	4.45 v.s.	4.5 v.s.	4.5 s.	4.5 s.	4.45 s.	4.5 m.s.	4.45 v.s.	4.45 v.s.
KI			4.1 w.	4.1 w.	4.20 w.			
I			3.8 w.	3.75 w.		3.7 v.w.		
K					3.52 w.		3.55 m.s.	
Q	3.33 m.s.	3.35 s.	3.35 s.	3.35 s.	3.35 s.	3.35 v.s.		3.35 w.
I	3.20 w.	3.20 w.	3.22 s.	3.20 s.				3.20
I	2.97 v.w.	2.98	2.98 w.	2.98 w.				
U	2.64 s.	2.64 s.	2.64 v.s.		2.62 m.s.	2.62 v.w.		
MKI	2.56		2.56	2.60 s.	2.52	2.52 w.	2.55 s.	2.60 m.s.
Q								2.48
I	2.44 w.	2.45 w.	2.45 m.	2.43 m.s.		2.45 v.w.		
KIQ						2.30 w.	2.35 w.	
MKI		2.26 v.w.	2.22 w.				2.23 v.w.	2.25 w.
I		2.17 v.w.				2.17 v.w.		
K	2.00		2.00 w.		1.97 v.w.			
K			1.83 w.		1.82 v.w.	1.83 w.		1.70 w.
MQ	1.70	1.70 w.	1.70 m.s.	1.70 w.	1.70 m.	1.70 w.		
KIQ	1.66		1.66	1.68	1.66		1.67 m.	
KQ	1.53 m.s.	1.53 w.	1.53 s.	1.53 m.	1.53 w–m.	1.53 w.		1.53 w–m.
MI	1.50 s.		1.50 s.	1.50	1.50 s.		1.50 v.s.	1.50
Q					1.38 w.	1.38 w.		
MKI	1.30 v.w.				1.29 v.w.		1.29 w.	
MKI	1.25 v.v.w.						1.24 w.	

* See footnote table 22.

the wide spacings (table 37), leaves some uncertainty as to the clay minerals present, although corresponding data for other colloids have led, in general, to conclusive identification.

As was pointed out earlier in the paper, all these colloids except the Maxwell are chemically similar to the San Joaquin clays, and especially is this true of those tabulated in table 36a. But the x-ray data show that this group of colloids is not characterized by any one type of clay mineral, as is the case

TABLE 36b

Interplanar spacings of Ramona, Placentia, and Maxwell colloids

MINERALS*	RAMONA 7091		PLACENTIA 7092		MAXWELL 17399	
	Air-dried	Heated to 500°	Air-dried	Heated to 500°	Air-dried	Heated to 500°
	Å.	Å.	Å.	Å.	Å.	Å.
M					15.1 v.s.	
IM	10.1 m.	10.1 m.s.		10.1 v.w.		9.8 m.
K	7.3 w.		7.3 w.		7.25 w.	7.3 v.w.
MI	4.45 v.s.	4.5 s.	4.5 s.	4.5 s.	4.5 s.	4.5 s.
I			3.7 v.w.	3.8 m.		
KI			3.6		3.6 w.	3.65 w.
I		3.4 w.	3.4 w.			
Q	3.34 s.	3.33 s.				3.35 w.
I	3.20 w.					3.20 w.
I	2.98 w.	2.93 w.				
U	2.63 m.s.					2.62 s.
MKI	2.56	2.60 v.s.	2.58 s.	2.58 m.	2.60 s.	
Q		2.50 w.		2.50 w.		2.46
I	2.43 m.	2.42 m.	2.40 w.			
Q		2.30 w-m.				
I			2.23 w.	2.25 w.		
I	2.18 w.	2.17 w.		2.17		
KI	2.00 w.	1.99 v.s.	2.00 w.			
M						1.72 v.w.
MQ	1.70 w.	1.70 w.	1.70 s.		1.68 w.	
KIQ	1.66	1.66	1.66			
KQ	1.53 m.s.	1.53 v.s.	1.53 w.	1.53 m.	1.53 w.	1.54 m.s.
IM	1.50 m.s.		1.50 s.		1.50 m.	1.50 w-m.
Q		1.37 w.				
MKI		1.32 w.			1.30 w.	1.30 w.

* See footnote table 22.

with most of those previously discussed in this paper. Excluding the Maxwell, which is of a different type, the other six samples show great diversity in their clay mineral content. Three show montmorillonite spacings, all but one show kaolinite spacings, and three show spacings associated with the "x" mineral. Only the Ramona and Placentia soils were found to contain clay minerals similar to those of the San Joaquin series.

The Madera pattern for the unheated material shows a definite but weak

montmorillonitic 15Å. spacing (table 36a). It is not surprising that a corresponding 9.5Å. spacing was not observed in the pattern for the heated material, as the reflection would necessarily be very diffuse and more or less merged with that of the near-by 10Å. spacing of the "x" mineral which the pattern contains.

In the high-temperature patterns for the Tujunga and the lower horizon of the Tule (sample 18891), the 9.7 and 9.9 spacings respectively, are taken to indicate the contracted montmorillonite spacing rather than the 10Å., the "x" mineral spacing, since with the low-temperature samples the 15Å. spacing was strong in both and the 10Å spacing was absent.

TABLE 37

Effect of partial dehydration on the interplanar spacings of various colloids

SERIES	SAMPLE NUMBER	TEMPERATURE	MONTMORILLONITE SPACINGS	KAOLINITE SPACINGS	"X" MINERAL SPACINGS
		°C.	Å.	Å.	Å.
Madera	6528	25	15.0	None	10.2
		500	None	None	10.0
Tujunga	7094	25	15.5	7.0	None
		500	9.7	None	None
Tule	18890	25	None	7.25	None
		500	None	None	None
Tule	18891	25	15.0	7.3	None
		500	9.9	None	None
Ramona	7091	25	None	7.3	10.1
		500	None	None	10.1
Placentia	7092	25	None	7.3	None
		500	None	None	10.1
Maxwell	17399	25	15.1	7.25	None
		500	9.8	7.3	None

It will be noted that the montmorillonite spacing is shown in the lower (sample 18891) but not in the upper horizon (sample 18890) of the Tule soil.

On the basis of the x-ray data in table 37, the Maxwell clay appears to contain both montmorillonite and kaolinite or similar clay minerals. In view of the origin of this material, however, the persistence of the 7Å. spacing in the heated material does not necessarily indicate kaolinite. The 7Å. line as well as other lines in the kaolinite pattern have been observed by the authors to persist even after heating to 500° for a considerable period, but it has been further observed that all kaolinite lines disappear completely if the heating to 500° has been sufficiently prolonged. Where kaolinite lines persist after

heating, a perceptible diminution in intensity is usual. In the present instance, the line representing the 7Å. spacing is weak in both the heated and the unheated material. Since the Maxwell soil is known to have originated from the weathering of serpentine rocks, it is pertinent to inquire whether the 7Å. spacing might be due to finely divided residues from serpentine minerals. It is known, for example, that chrysotile, a mineral in the serpentine class, contains a spacing of 7.32Å. which, on the basis of cell dimension data by Bragg (4), has Miller indexes (200). We intend to investigate more fully the possible presence of serpentine residues in the colloidal clay minerals.

The data in tables 36a and 36b show strong reflections due to quartz spacings in four of the seven colloids, but with the three remaining colloids, the indications of quartz were much less definite. These colloids are almost entirely free from spacings other than those of the clay minerals and quartz.

DISCUSSION

It is worthy of note that the colloids of a high percentage of the soils studied in this investigation were found to be decidedly heterogeneous. This heterogeneity involves both the kind of clays and the minor amounts of other classes of minerals which they contain. Although the colloid of every soil examined was composed chiefly of clay minerals, more than one type of clay mineral was usually present in a given sample. With but few exceptions, however, the colloid of each soil appears to be dominated by a single type of clay, but it should be emphasized that too few soil profiles were included in this study to warrant definite conclusions as to the specific type of clay that is characteristic of given soil series. The results indicate that in the Yolo series montmorillonitic clays predominate; in the Redding, Sierra, Vina, Keefers and Tule series, kaolinitic clays appear to predominate; and in the San Joaquin and Hanford soils the clay is more largely of the muscovitelike type, referred to herein as "x" mineral.

It should be emphasized that the word "montmorillonite," as used in this paper, refers not to the specific mineral, montmorillonite, but rather to the group to which this mineral belongs. This group includes montmorillonite, beidellite, nontronite, and probably saponite, all of which appear to be characterized by the shifting position of one of their diffraction lines, depending on the water content of the sample. We have merely made use of this property for the purpose of identification.

The kaolinitic clays, as used herein, include both kaolinite and halloysite. It is possible that halloysite was the chief member of this group in the soils studied. Mehmel (30) showed that halloysite loses water at 50°C., passing into metahalloysite, which is very similar structurally to kaolinite. Hendricks (16) has recently shown that hydrated halloysite loses water, apparently irreversibly, upon standing in the laboratory. He suggested that the ordinary form of halloysite is probably identical with Mehmel's metahalloysite. Since the soils reported in this paper were taken from comparatively dry and hot

climates, any halloysite that they contain was probably the partially dehydrated form, which is difficult to distinguish from kaolinite.

With a large percentage of these colloids, base-exchange capacity was found to be roughly proportional to SiO_2-Al_2O_3 ratio, which agrees with previously published results of other investigations. This correlation, however, was far from perfect, and a few marked exceptions were found. For example, samples 18889, a San Joaquin clay, and 16054, a Vina sample, have the same SiO_2-Al_2O_3 ratio, but their base-exchange capacities differ more than 50 per cent (40 vs. 61.7); and colloid 6530, another San Joaquin sample, with a SiO_2-Al_2O_3 ratio of 3.20, has a base-exchange capacity of only 27.6, whereas 16055, a Vina sample, has a ratio of 2.94, and yet its capacity was 64, which is one of the highest found in the entire list of 44 colloids investigated. Since the samples were distinctly heterogeneous in mineral composition, a close correlation between the SiO_2-Al_2O_3 ratio and base exchange is not to be expected. Quartz, in minor and probably variable amounts, was present in all the samples; moreover, the other nonclay minerals, together with any amorphous SiO_2 that was present, would certainly exert some influence on the SiO_2-Al_2O_3 ratio and thus tend to upset the correlation with base-exchange capacity. Moreover, the distribution of particle sizes may have differed substantially in the different samples, and this might affect base-exchange capacity to some extent.

The ratio of SiO_2 to R_2O_3 is influenced by a factor additional to those already mentioned, namely, uncombined Fe_2O_3. Analysis of the buffered acid extracts obtained in the treatment of the samples for the special optical studies reported in table 19, showed that 50 or more per cent of the total iron is uncombined in these colloids. The color of the samples before acid treatment was red, after treatment, gray. In view of these facts, it is obvious that the SiO_2-R_2O_3 ratio can give but the merest suggestion as to the specific minerals present. Of course, with strongly lateritic colloids, such as the Nipe (8), this ratio indicates that much of the sesquioxide is present in nonsilicate form. The mere presence of uncombined Fe_2O_3, however, is hardly a useful criterion of laterization, since uncombined Fe_2O_3 is probably present in variable amounts in most soil colloids.

There appears to be no definite relation between content of nonreplaceable forms of the ordinary bases and base-exchange capacity or other properties of these colloids. It is true, the montmorillonitic types tended to be relatively high in Mg, the Yolo and Maxwell clay colloids being the highest in total Mg found. However, the colloid of the B horizons of the Palermo Redding samples, although predominantly montmorillonitic and high in base-exchange capacity, contain much less Mg than the Yolo and Maxwell clays. Moreover, the Ramona, Placentia, Tujunga, and Madera clays are not predominantly montmorillonitic, nevertheless they contain more Mg than the Palermo Redding colloids. As is well known, the bentonitic clays usually contain Mg, but as will be shown in another paper, their base-exchange properties are not

proportional to Mg content. It seems doubtful whether Mg plays any important part in the base-exchange properties of these colloids.

Neither is the content of K a significant index to the properties of these colloids. Those which contain the highest proportions of mineral "x" tended to be relatively high in K, but the same is also true of Yolo samples 431 and 7083, neither of which contains significant amounts of mineral "x." It is likely that K was present in these colloids, in part at least, as a constituent of accessory minerals other than the true clays. The mineral "x" may possibly contain K as an essential constituent.

Moreover, K content of these colloids is not directly proportional to the maturity of the profile. For example, the Davis Yolo clays, although obtained from a soil which shows very feeble profile development, contain less K than the colloid of the Keefers, which is a highly weathered and mature soil. This, of course, need not occasion surprise, since the parent material of the Davis Yolo soil is composed of comparatively recent alluvium, some, at least, of which may have been eroded from areas that had already undergone extensive weathering and leaching before being transported to the Davis area. It is probable that, among soils of common origin and similar geological history, the content of K and Na will bear some direct relation to intensity of leaching, but the soils studied in this investigation do not meet this requirement. As has been pointed out, the Ca content of these colloids was mainly determined by their base-exchange capacity, but the amounts of Ca found afford but little clue to pedological processes, since the samples were artificially saturated with Ca. The ratio of bases to SiO_2 or sesquioxide in these colloids is, therefore, of doubtful significance.

Particular attention has been paid to the Vina samples, in view of the fact that their base-exchange capacity is relatively high, despite their kaolinitic nature. A sample was separated into two fractions, namely, particles from 1.0–0.25 μ in diameter, and those less than 0.25 μ, but no material difference was found in their chemical composition, base-exchange capacity, or x-ray properties. The same x-ray lines were produced by each, and those of the coarser (0.25–1.0 μ) fraction were no more distinct than those of the finer fraction. The conclusion seems reasonable, therefore, that the faintness of the x-ray lines produced by this type of colloid was probably not due to its being composed of exceptionally small sized particles. It is more probable that this colloid is less well crystallized than most of the other types studied.

As shown in the section on x-ray investigation, two of the samples of Vina colloid gave some evidence of montmorillonitic clay, in addition to the much greater amount of the kaolinitic type. The relative proportions of the two types of clay cannot now be estimated. We can only say that the kaolinitic lines were much stronger than those of the montmorillonitic lines, and that the latter were much weaker than those of the Yolo clays, which are clearly predominantly montmorillonitic.

The fact that the two fractions of the Vina clay, referred to above, have almost identical base-exchange capacity and chemical composition is in har-

mony with the recent results of Hauser and Reed (15) on Wyoming bentonite; but they disagree with the results which Marshall (29) obtained with one bentonite and two soil colloids, those of Whitt and Baver (37) on Putnam Clay, and also those of Bray (7) on colloids from Illinois.

Among the colloids investigated, there appears to be no dependable correlation between kind of clay mineral and base-exchange capacity. It is true, the montmorillonitic types all have relatively high base-exchange capacity, whereas certain kaolinitic types have low base-exchange power. But the Vina samples, one of which appears to contain no clay mineral except the kaolinitic type and the other two of which are predominantly kaolinitic, all have about as high base-exchange capacity as the montmorillonitic types. Moreover, certain of the more purely kaolinitic types, the Keefers, for example, have comparatively high base-exchange capacity, and the Hanford and San Joaquin samples gave still higher figures for base-exchange capacity, yet their clays are predominantly of the muscovitelike type and, for the most part, virtually free from montmorillonitic clay.

These results are difficult to harmonize with the idea that, apart from organic matter, base exchange in soils is due either to a single chemical substance or to one type of clay mineral. The results also bear on the question as to the position of the exchangeable ions on the lattice, but this question will not be discussed here.

The reference to the size of the grains and flakes, observed in the optical studies, should not be confused with the previous statement that the upper limit of particle size was approximately 1 μ. These comparatively large grains and flakes were composed of many small particles which coalesced and partially oriented during the processes of Ca saturation and drying. Proof of particle size was obtained by direct microscopic observation on an aqueous suspension of Na-saturated samples of several different colloids. It was found that a 0.1 per cent suspension of the Na-saturated form was, in every case, composed of particles 1μ or less in diameter. As is well known, Na-saturated colloids are usually much more completely dispersed than the Ca form. Gedroiz (11) showed, for example, that Na saturation of certain Russian soils substantially increased the clay content as found by mechanical analysis.

This investigation shows that it is possible to arrive at a fairly definite understanding of soil colloids by using a combination of methods of study. The four independent methods used in this work; namely, chemical analysis, dehydration, optical, and x-ray investigation, usually gave consistent results. The indications afforded by this work are that a thorough study of the colloid, not only will throw important light on the general properties of the soil, but may also be utilized as a material aid in soil classification.

It is especially interesting that in certain profiles of the Redding and also the Tule series, the relative content of montmorillonitic clay tends to increase with depth. The same tendency has recently been found in a Susquehanna profile (25).

In view of the wide differences in the clay mineral content of the colloids

of the different soil types, which in turn probably caused variations in base-exchange capacity, the thermal loss of water, particularly at 100°C., and probably differences in swelling upon wetting and contraction upon drying, it is hardly likely that the water regimes and crop responses of different soils will be definitely correlated with total clay content. It is virtually certain that the surface soil of Yolo loam, for example, has properties significantly different from those of Sierra or Redding loam. In this connection, it is important to remember that, in all probability, the variable nature of the noncolloidal constituents which are known to occur in soils also exerts important influences. These constituents, together with the variable physical nature of the profile of different soil types, all influence crop production.

SUMMARY

The colloids of the Yolo and the San Joaquin family of soils (San Joaquin, Ramona, Placentia, Hanford, and Tujunga) were found to contain substantial amounts of nonexchangeable Mg, and the Maxwell clay is exceptionally high in Mg. Base-exchange capacity, however, is not proportional to Mg content. For example, two of the Vina clays are low in Mg but high in base-exchange capacity. Nonexchangeable Na was low in every sample investigated, and K also was comparatively low. The San Joaquin clays and certain of the Hanford and Yolo samples were the highest in K found.

The SiO_2-Al_2O_3 ratio of the Yolo and of certain samples of the San Joaquin series was approximately 4, whereas that of the Sierra, Keefers, and certain Redding profiles approached 2. This ratio in most of the other samples lies between 2 and 4. In the Maxwell it was found to be almost 5. Although there is a rough proportionality between SiO_2-Al_2O_3 ratio and base-exchange capacity, the correlation is not high, and in certain cases it appears to be negative.

The dehydration curves appear to be somewhat characteristic of each type of colloid, the shape of the curve depending very largely on the kinds and relative proportions of the different clay minerals present. The dehydration curves of the Yolo and Maxwell clays resemble those of the bentonitic clays, and the curves for the Sierra, Keefers, and certain Redding samples are similar to the curves for kaolinite and halloysite. A relatively good correlation was found between water loss at 100°C. and 150°C., respectively, and base-exchange capacity.

Their optical properties show that these colloids are preponderantly crystalline. The birefringence (gamma minus alpha) was approximately .020 in the Yolo and in the B_2 horizon of the Redding from Palermo. The birefringence of the Tujunga, Hanford, Ramona, Placentia, San Joaquin, and Madera clays was also comparatively high. Those colloids with low SiO_2-Al_2O_3 ratios also have low birefringence. Quartz was found in every sample, and rutile and zircon were tentatively identified in several samples.

Saturation with Ca, Mg, K, or Na appears to have but little influence on the optical properties of these colloids.

In the air-dried condition the ultimate particles of these colloids arrange themselves in the form of comparatively large flakes or grains, which appear to act as single optical units in all respects except one, namely, these flakes were crowded with minute inclusions which have optical properties altogether different from those of the flakes as a whole. In aqueous suspension these flakes tend to break down. The Na-saturated form, when studied in a dilute suspension, showed scarcely any large flakes. Instead, all visible particles were approximately 1 μ or less in diameter.

Removal of the more soluble and probably uncombined Fe_2O_3 lowered the indexes of refraction in all samples studied.

X-ray analysis showed that every colloid studied is definitely crystalline and composed chiefly of clay minerals of different types. The Yolo and Maxwell clay colloids are predominantly montmorillonitic; the Sierra, Redding, Vina, and Keefers colloids are preponderantly kaolinitic; and the San Joaquin and Hanford colloids are largely composed of the "x" clay mineral, similar to illite. Certain samples from different soil types were found to be composed of mixtures of these clay minerals.

The optical properties, while less diagnostic, are consistent with the conclusions from x-ray study. It is thought that the high indexes of refraction are due to admixed iron oxide, and that the occasional high double refraction found, for example, in certain Redding clays, may indicate "form double refraction."

In addition to the clay minerals, x-ray investigations showed that quartz was also present in minor amounts in every sample, and rutile and zircon were probably present in certain samples.

It is possible to determine the types of clay minerals present in soil colloids by comparing the x-ray diffraction patterns with those of known minerals. The determination is especially facilitated by x-raying the samples at widely varying moisture content. The dehydration curves of the different clay minerals show that OH lattice constituents pass off as water vapor at temperatures which are characteristic for each class. The consequence is their x-ray diffraction pattern is destroyed at these temperatures.

One of the most characteristic x-ray lines of the montmorillonitic clays corresponds to a spacing of about 15Å. in the air-dried form of the clay and of from 9.5 to 10Å. in the material heated to 500°C. The diffraction line characteristic for the identification of the kaolinitic clays corresponds to a spacing of about 7.0Å.; this spacing is not affected by heat treatment below the temperature of decomposition, but at about 500°C. this, as well as the other lines of these clays, disappears as a result of decomposition. The corresponding line of the "x" mineral is found at about 10Å. and remains in this position until the sample is heated above 500°C. By combination of partial dehydration with x-ray analysis, therefore, it is possible to determine what clay mineral is present, whether alone or as mixtures of other types of clays. If crystalline minerals other than the clays are present, their identity can, in some cases at least, be established by reference to the diffraction patterns of known minerals.

While x-ray analysis affords a means of identification of the several classes of minerals present in soil colloids, it does not necessarily yield all the important information about soil colloids. A combination of two or more types of methods is the more instructive.

In view of the fact that many California soil types were not included in this work, and that an inadequate number of samples of several of the types used were studied, the conclusions drawn in this paper should be regarded as tentative. Much further work will be required for a full elucidation of this subject.

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MINERALS PRESENT IN SOIL COLLOIDS: I. DESCRIPTIONS AND METHODS FOR IDENTIFICATION

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The clay fraction of soils has long been recognized as playing an important part in determining the properties of soils. Early methods for studying this fraction were chiefly restricted to chemical analyses because the small particle size did not permit application of mineralogical technics then available. Chemical analyses showed that the principal constituents of the colloids are oxygen, silicon, aluminum, and iron, with lesser amounts of magnesium, potassium, sodium, calcium, and titanium. But the manner of combination of these constituents could not be determined from the chemical composition, and analytical methods now are recognized as giving only partial information on the question of mineral composition.

It was not until the application of x-ray diffraction that the essential crystallinity of the colloidal fraction of soils was fully demonstrated, although a few mineralogists had recognized the fact, and possible combinations of the constituents were determined. This development was made possible by the rapid advance in knowledge of the structures and ranges of compositions of the clay minerals. Applications of methods now available make possible identification of the major inorganic components of soil colloids and semiquantitative estimation of their amounts.

Although much work has been done on the mineralogy of the clays, the nomenclature of some of the groups is still confused and there is doubt about some of the details of crystal structures. It is a purpose of this article to attempt a presentation of the subject suited to the needs of the soil scientist. Methods adequate for identification of the mineral constituents of soil colloids also are described in this paper and will be illustrated by application to a group of soil colloids in the following paper.

THE CLAY MINERALS

Though the older literature on clays is extensive, the major progress has been made in the last decade. Several articles reviewing recent work have appeared (8, 19, 21, 24, 25, 26, 29), and considerable analytical data have been summarized by Von Engelhardt (8). Much of the extensive work of Dr. C.

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S. Ross, of the U. S. Geological Survey, has not yet been published, however, and a number of crystal structure determinations of clay minerals made in the U. S. Bureau of Chemistry and Soils have not appeared. The following summary depends in part upon this unpublished work and upon many discussions with others.

Classification of clay minerals necessarily depends upon their crystal structures, but it is perhaps best to direct attention first to changes in their chemical compositions as affected by substitution of one element for another, that is, by isomorphous replacements. Such changes are well illustrated by the micas, in which they are very extensive. Although these were known to early mineralogists, it was only after the x-ray investigations of Maugin (27) that the kind and extent of the replacements were fully realized. The ideal[3] composition of muscovite can be expressed as

$$K\,[Al_2]\,[AlSi_3]\,O_{10}(OH)_2 \text{ or } \tfrac{1}{2}\,(K_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O)$$

the brackets enclosing groups of atoms which occupy similar positions in the crystal lattice. Isomorphous replacements in muscovite as well as other minerals are determined more by the relative sizes of the various ions than by their chemical similarities. Thus potassium in muscovite can be replaced to a limited extent by the somewhat smaller sodium ion but not by the much smaller lithium ion. Aluminum, enclosed in the first bracket, is surrounded by six oxygen and hydroxyl ions at the corners of an octahedron. It can be replaced by Ti^{+2}, Fe^{+3}, Fe^{+2}, Mg^{+2}, Mn^{+2}, Mn^{+3} and Li^{+3}, which are similar to it in size. Electrical neutrality is maintained by accompanying changes, thus $[Al_2^{+3}]$ can be replaced by $[Mg_3^{+2}]$, leading to mica phlogopite. Silicon in the second bracket has tetrahedral coordination and can only be replaced by aluminum. There can be simultaneous replacements of the type

$$K, Si \rightleftarrows Ca, Al$$

the Ca, Al mineral being the brittle mica, margarite. Finally, hydroxyl can be replaced by fluorine, and oxygen can sometimes be substituted by hydroxyl. These replacements must be given careful consideration since they depart greatly from chemical expectations and seriously affect the manner in which oxide ratios such as R_2O_3:SiO_2 should be regarded.

The clay minerals which are common constituents of soil colloids can be divided into three general groups: (a) kaolin minerals, (b) montmorillonites, and (c) hydrous micas. These will be discussed in the order given.

The kaolin minerals

The mineralogy and compositions of the kaolin minerals have been extensively studied by Ross and Kerr (32, 33), who have discussed the various

[3] The term "ideal" is used for the chemical formula that serves as a basis for discussion of isomorphous replacements. It is usually called "the end member of a series" by mineralogists and represents an approach to the composition associated with the mineral name.

names that have been used. The ideal composition is

$$[Al_2]\,[Si_2]\,O_5(OH)_4 \text{ or } Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$$

and there are four polymorphic varieties: (a) kaolinite, (b) nacrite, (c) dickite, and (d) halloysite. Isomorphous replacement in these minerals is largely restricted to mutual substitutions of Al and Si in the $[Si_2]$ positions, with resulting variation in $SiO_2:R_2O_3$ ratio from 1.6 to 2.9:1, as shown by Ross and Kerr. Ratios below 2.0 are a result of replacement of Si by Al with accompanying changes in $[Al_2]$ positions or substitutions of oxygen by hydroxyl. It is not known on the basis of structure how ratios greater than 2.0 come about, and kaolinites with such ratios are usually called "anauxite." Particular attention is directed to the fact that kaolin minerals do not contain appreciable iron or magnesium, neither of these exceeding one mol per cent.

Only kaolinite and halloysite have been reported as occurring in soils, nacrite and dickite being of hydrothermal origin. Another mineral related to the kaolins is hydrated halloysite, the composition of which can be represented as

$$Al_2O_3 \cdot 2SiO_2 \cdot 4H_2O$$

This mineral easily loses two molecules of water by air drying from the above formula, changing to halloysite which has not been rehydrated in the laboratory. It has not been observed as a constituent of soils.

Montmorillonites

Analyses of montmorillonites are listed by Von Engelhardt (8), Hofmann and Bilke (16), and Nagelschmidt (28). A more extensive collection together with mineralogical characteristics and a discussion of nomenclature will soon be published by Dr. C. S. Ross. The ideal formula is

$$[Al_2]\,[Si_4]\,O_{10}(OH)_2 \cdot xH_2O \text{ or } Al_2O_3 \cdot 4SiO_2 \cdot H_2O + xH_2O$$

and the same types of isomorphous replacements as outlined for mica take place. Substitution of $[Al_2]$ by $[Mg_3]$ gives the formula $Mg_3Si_4O_{10}(OH)_3 + xH_2O$, which is that of the mineral magnesium bentonite (9). The name "bentonite" is often used as synonomous with "montmorillonite," but more strictly it refers only to material derived from volcanic ash and might sometimes be related to the micas rather than to the montmorillonites; that is, bentonite is a rock rather than a mineral name. Analyses have been published in which the amount of SiO_2 exceeds that required by the above formulas, but this condition probably always results from the presence of silica as an impurity, as has been definitely proved for a number of samples. Substitution of $[Al_2]$ by $[Fe_2]$ leads to the mineral nontronite with the ideal formula $Fe_2Si_4O_{10}(OH)_2 \cdot xH_2O$, the Fe being predominantly ferric. In any of these minerals, silicon in tetrahedral coordination can be replaced by aluminum, and the $SiO_2:Al_2O_3$ ratio (the Al_2O_3 including the isomorphous replacement) can approach 2:1, a possible formula being

$$[Al_2]\,[AlSi_3]\,O_9(OH)_3 \cdot xH_2O$$

or, instead of oxygen's being replaced by (OH), further ions can be substituted with octahedral coordination; that is, in the [Al_2] positions. These minerals are usually called "beidellite," the SiO_2:(R_2O_3 + RO) ratio in many instances being near 3:1.

The structure studies of Hofmann and his associates (16, 17, 23) have shown the manner in which montmorillonites reversibly take up water between the alumino-silicate layers of the lattice. This water is represented by xH_2O, being indefinite in amount, in the above formulas and accounts for the swelling properties of the minerals. Montmorillonites are further of interest in that they show greater base exchange capacity than do the other clay minerals. The calcium, the amount of which usually is much less than that of magnesium in montmorillonites, apparently is present as exchangeable ions which are external to the lattice and should not be considered an essential part of the formula.

Hydrous micas

At present it is debatable what name should be given to the clay minerals related to the micas. These minerals were first recognized as components of soil colloids by Hendricks and Fry (15) under the name "ordovician bentonites," a term that had been used by Ross and Shannon (34). They have now been investigated very thoroughly by Grim, Bray, and Bradley (10) and by Hofmann and his co-workers (7, 18). The former group of authors used the name "illite"; and the latter, "glimmerton" or the "micalike mineral" of the clays. Other names that have been used include "bravisite," and "hydromica" (7, 10, 18). Glauconite is probably a related mineral.

The ideal formula can be considered to be the same as that given for mica, but the minerals always contain less potassium and more water. Grim, Bray, and Bradley give the formula

$$2K_2O \cdot 3R'O \cdot 8R_2''O_3 \cdot 24SiO_2 \cdot 12H_2O$$

as representing the average of their analyses of illite. The composition is obtained from the ideal mica formula

$$K\,[Al_2]\,[AlSi_3]\,O_{10}(OH)_2$$

by replacement of K by H_2O accompanied by substitution of Si for Al in tetrahedral coordination, or (OH) for O to keep the charge balanced. These minerals contain appreciable Mg and Fe (both ferric and ferrous) replacing [Al_2] with octahedral coordination and thus are more closely related to biotite than to muscovite. The amount of K_2O is very variable, the total range being from the order of 1 per cent to that required for muscovite (11.8 per cent K_2O). Many of the analyzed samples, however, contain almost 5 per cent K_2O, which can be taken as an average value.

Glauconite, the essential component of greensands, is perhaps the mineral of this type that has been recognized for the longest time. Both its iron

and potassium contents are greater than those of the material described as illite, and its water content is less. Glauconite thus more closely approaches the mica biotite in composition, and its close structural similarity to biotite has been demonstrated (13).

Particular attention is directed to the work of Denison, Fry, and Gile (5) on the alteration of muscovite and biotite in the soil. These investigators followed changes in composition of the coarse-grained micas undergoing weathering. Their many analyses of samples selected with mineralogical control show continuous variations from the pure micas through the glauconite and illite ranges. The weathering of mica in the soil is accompanied not only by decrease in potassium and increase in water content but also by decrease in iron and magnesium with accompanying increase in aluminum.

Perhaps it is evident from this discussion that the gradation in composition is so continuous as hardly to justify the naming of intermediate minerals. For this reason the entire series will simply be referred to as "hydrous micas," since this name shows their relationship to the micas while indicating the nature of departure. "Hydromica" can not be used as a name, since it has been used in other ways in mineralogical literature.

Kaolins, montmorillonites, and hydrous micas, as well as micas, brittle micas, chlorites, brucite, vermiculite, talc, and a number of other minerals[4] that do not occur in soil colloids have closely similar structures, as was first shown by Pauling (31). They all contain alumino-silicate layers (with isomorphous replacements) between which there is perfect cleavage, and individual crystals contain many superimposed layers. Gruner (12) has shown that minerals can be formed by interstratification of different kinds of layers. He gave the name "hydrobiotite" to such a composite of vermiculite and biotite, the composition being similar to that of hydrous micas. This type of mixed mineral is difficult to recognize, but it is probably a common constituent of soils. In particular, montmorillonites and hydrous micas probably occur together in a manner similar to Gruner's hydrobiotite. In fact, it is somewhat questionable that individual montmorillonite crystals are common constituents of soils although they undoubtedly are present in some.

Accessory minerals of soil colloids

Free oxides and free hydrous oxides of iron are common constituents of soils, to which they impart red or yellow color. The common minerals present are hematite, Fe_2O_3, and goethite, FeO(OH). Goethite is often called "limonite," a name that includes not only goethite but also amorphous material approximating FeO(OH) in composition as well as lepidocrocite, which has not been identified in soils.

There has been some discussion as to the state of combination of the titanium which is always present in soil colloids in amounts of the order of 0.5 per cent or greater. It frequently has been suggested that the titanium is chiefly in

[4] See Bragg (3, p. 203–229) for a clear discussion of the structure of these minerals.

combination with the silicates, replacing aluminum (35). Though some of it is undoubtedly in this form, it is probable that separate titanium-bearing minerals are present, particularly leucoxene, the composition of which is indefinite. Alteration of titanium minerals such as ilmenite to leucoxene has been observed microscopically in coarse fractions of unconsolidated materials.

It is probable that other minerals are occasional constituents of soil colloids. Among these are the oxides of aluminum such as the minerals diaspore, AlO(OH), böhmite, AlO(OH), and Gibbsite or hydragrallite $Al(OH)_3$, which are components of bauxite. Quartz (SiO_2) is probably always present, but its amount depends strongly on the upper particle size limit chosen in separating the soil colloid. It is possible, too, that amorphous silica might sometimes be present as a minor constituent. Calcium carbonate in the form of calcite is sometimes present, as also are phosphorus-bearing minerals.

METHODS FOR IDENTIFYING AND ESTIMATING COMPONENTS OF SOIL COLLOIDS

Chemical methods

It is evident from the foregoing discussion that the $SiO_2:R_2O_3$ ratio of the soil colloid must be used with extreme caution for identification of the component minerals since they overlap in this ratio and since some of the oxides, particularly those of iron, may or may not be combined with silica, and silica may be free. If analyses are made after removal of free oxides of iron and it is borne in mind that aluminum can be replaced by magnesium, and iron, then the hydrous micas and montmorillonites generally have a higher $SiO_2:(R_2O_3 + RO)$ ratio than kaolinite or halloysite, as well as a higher $SiO_2:Al_2O_3$ ratio. Since most colloids are mixtures of these minerals, however, no great use can be made of such ratios for identifying the mineral components.

Free oxides of iron in a soil colloid can be readily removed and determined by the use of nascent H_2S according to the method of Truog and his associates (36). If the amount of iron combined with silica as found in this manner exceeds 2 per cent Fe_2O_3, hydrous micas, montmorillonites, or their mixed layer minerals are present. Absence of combined iron does not indicate, however, that these minerals are absent, as is evident from the discussion of their compositions.

Determination of nonexchangeable potassium gives information on the presence of hydrous mica, as potassium is an essential constituent only of this mineral among the common minerals of the soil colloid. It has already been pointed out that the potassium content of hydrous micas is variable and this limits the use of the analytical data for quantitative estimation. Colloids containing more than 1 per cent of nonexchangeable potassium, as examined to the present time, have hydrous micas as a prominent constituent.

Magnesium can be extensively substituted for aluminum in the clay minerals other than those of the kaolinite group, and such minerals are present when the amount of nonexchangeable magnesium in the colloid is appreciable, exceeding about 1 per cent. Thus determination of magnesium gives the same type of information as does determination of iron combined other than

as oxides. It is best, however, to know both, since one or the other replacement might predominate. It further should be emphasized that calcium does not replace magnesium in the clay minerals and when present other than as carbonate, sulfate, or phosphate, is exchangeable.

X-ray diffraction methods

X-ray studies have been most useful in showing that the colloidal fraction of soils predominantly contains crystalline clay minerals and in determining the structure of these minerals. Observations on soil colloids are restricted to powder diffraction patterns which are used in a strictly empirical manner by comparison with known minerals. Isomorphous replacements such as those found in the clay minerals affect the patterns only slightly, the greatest effect being produced on intensities by substitution of iron for aluminum.

TABLE 1

Characteristics of reflections from the cleavage planes of clay minerals occurring in soil colloids

MINERAL	KAOLINITE	HYDROUS MICA	MONTMORILLONITE, AIR-DRIED (19)
Spacing of (00n)	7.1	10.0	15.0
Intensity of n*	s†	ms	vs
2 n	vs	m	m
3 n	w	vs	a
4 n	w	w	a
5 n	vw	s	s
6 n		vw	a

* Intensities are for Cu Kα radiation in cylindrical camera of type shown in plate 1.

† The following abbreviations are used: n, the order of the spectrum; s, strong; m, medium (ms); w, weak; a, absent; v, very (vw, vs).

Ordinary powder diffraction data for the clay minerals have been given in several places (14), suitable references being for kaolinite (11, 15), hydrous mica (7, 10, 15), and montmorillonite (15, 17). Since the clay minerals have many structural elements in common, this type of data is not the best for differentiating them. Their most characteristic differences are in their interplanar spacings normal to the plane of perfect cleavage [(001) in crystallographic nomenclature].

Clay minerals, being micaceous in habit, separate from suspensions with many of the individual plates approximately parallel to the surface on which they settle. The spacings of (001) can best be obtained from such oriented samples, and the type of camera described by Clark, Grim, and Bradley (4), which is illustrated in plate 1, is well suited for this purpose. Values for the cleavage spacing of the three types of clay minerals common in soil colloids are listed in table 1 together with intensities of the various orders of reflection.

The (001) spacing of montmorillonite varies with water content (17, 23), and this variation can be used as an aid in identification. Irrespective of water content, however, the second most intense reflection has a spacing near

3.0 Å., which is always less than the spacing of the second observed order from kaolinite. This reflection can be confused with the intense third observed order from hydrous mica.

Hydrous mica and kaolinite can be identified with certainty by use of the oriented samples. The mixed layer minerals, however, have a strong reflection with a spacing of about 3.0 Å., and this is confused with that of montmorillonite. As a practical matter, the identification of montmorillonite is difficult because of these confusing factors.

The crystal lattices of kaolinite and halloysite are destroyed by heating, with accompanying loss of water, at lower temperature than are those of montmorillonite and hydrous mica. Resultant changes in diffraction patterns after heating to 500° have been utilized by Kelley and Dore (20) for identifying these various minerals. Though their procedure is very useful, it could be improved by removing the decomposition products of kaolinite resulting from the heating before making x-ray diffraction photographs. As has been indicated, these photographs should preferably be made from oriented samples.

X-ray diffraction patterns of kaolinite and halloysite are closely similar, but recognized mineral specimens of the two give perceptibly different results. The pattern of the kaolin mineral common in soils most closely resembles that of kaolinite. The possible presence of halloysite cannot be eliminated, however, and for this reason no distinction is made between the two which are classed together as kaolinite.

It is desirable to remove the free oxides and hydrous oxides of iron as well as the organic matter before preparing the oriented samples, since these materials both obscure the pattern and interfere with the orientation. Their removal also permits use of Cu K α radiation, in making the diffraction photographs, which is more normally available in x-ray laboratories. Relative amounts of each of the clay minerals present in soil colloids can be estimated from the intensities of reflections given by the oriented samples. The accuracy obtained, however, is low.

A component present in a mixture of the type of soil colloids may not be detected in amounts less than 2 per cent. Only a few tenths of a gram of material is needed for the x-ray work, and if necessary this work can be done on a few milligrams.

Water content of clays and thermal analysis

Water is an essential constituent of all the clay minerals and plays an important part in their structures and behavior. It enters both as H_2O molecules and as (OH) groups, as is indicated by the ideal formulas which are repeated here for the sake of clarity:

Kaolin	$[Al_2]\,[Si_2]\,O_5(OH)_4$
Hydrous micas	$K\,[Al_2]\,[AlSi_3]\,O_{10}(OH)_2 \cdot xH_2O$
Montmorillonite	$[Al_2]\,[Si_4]\,O_{10}(OH)_2 \cdot xH_2O$

All of these minerals show considerable adsorption of water. The amount of adsorbed water, as well as the water between layers of montmorillonite and possibly of hydrous mica, depends upon the humidity. In fact, change in weight of a soil colloid as a function of humidity (2) will probably be useful in detecting montmorillonite and mixed layer minerals containing montmorillonite layers.

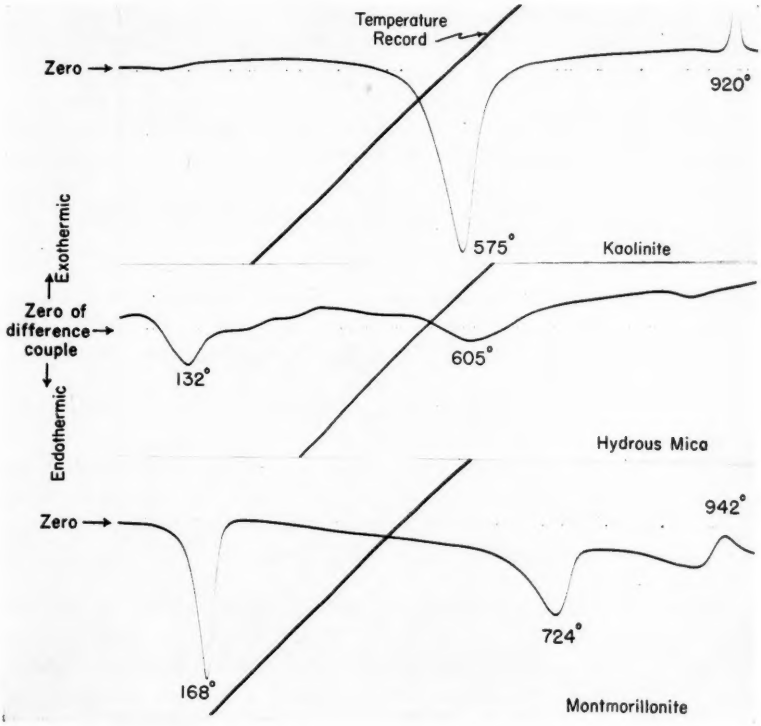

FIG. 1. DIFFERENTIAL THERMAL ANALYSIS CURVES FOR KAOLINITE, HYDROUS MICA, AND MONTMORILLONITE

When clay minerals are heated they lose their water at various temperatures characteristic for each mineral, as shown by Le Chatelier more than fifty years ago (22). Several different methods have been developed for following changes in water content, as a sample is heated. One of these is simply to measure the loss in weight as the sample is heated to constant weight at various temperatures. Another is to follow the change in weight when the specimen is heated at a more or less constant rate (6). Perhaps the simplest is the differential thermal analysis used by Le Chatelier, which is to follow the temperature of a sample relative to that of an inert material as the two are heated at the

same rate. An endothermic change is accompanied by a lag in the temperature of the sample; an exothermic change, by an increase relative to the inert material.

A suitable apparatus for differential thermal analysis patterned after one used by Norton (30), of the ceramics department of the Massachusetts Institute of Technology, is shown in plate 2. The heating rate generally used in this work is from 10–20°C. per minute, and it is necessary to raise the sample to about 1000°C. Both the differential and furnace temperatures are recorded photographically, a suitable type of recording drum being shown in the plate. Small quantities of material are required, less than 0.5 gm. being sufficient.

Differential heating curves for kaolinite, montmorillonite, and hydrous mica, are reproduced in figure 1. The nature of the changes in kaolinite upon heating are discussed as an example. Below 200°C. kaolinite loses adsorbed water endothermically, and there is some incidental change caused by differences in heat capacity, compaction, etc. relative to the inert material. The most characteristic feature is the endothermic loss of water of composition between 550–600°C., and this can safely be used as a criterion for a kaolin material and as a basis for its semiquantitative estimation. After the loss of water the sample is amorphous and the exothermic change between 950–1000°C. accompanies recrystallization of the aluminum oxide as γ Al_2O_3.

The most characteristic features of the montmorillonites and hydrous micas are their endothermic loss of water below 200°C. and near 700°C. There are considerable variations for different samples at the lower temperature and danger of confusion with adsorbed water. The endothermic reaction of montmorillonite near 700°C. is small compared with that of kaolin near 580°C. and is not sufficiently different from that of hydrous mica to allow an unambiguous distinction between the two.

Although thermal analysis for identification of clay minerals can be applied to the untreated soil, as has been done, for instance, by Agafanov and Jouravsky (1) for a group of soils from Tunis, it is very desirable to remove the organic matter, since this burns exothermically over a wide region, sometimes obscuring kaolinite. It is not absolutely necessary to separate the colloid, especially in heavy soils where it is a considerable fraction of the soil.

SUMMARY

The nature and compositions of minerals present in the colloidal fractions of soils are discussed, and methods are described for identifying these minerals. The most common components of soil colloids are kaolin minerals (kaolinite or halloysite), hydrous micas, montmorillonites, quartz, goethite, and hematite. These can be identified and their amounts estimated by simultaneous use of suitable chemical analyses, x-ray observations, and behavior upon heating. X-ray measurements, though desirable, are not indispensable, and methods,

although somewhat inadequate, for identification of clay minerals can readily be carried out in most soil laboratories.

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PLATE 1

CAMERA FOR MAKING X-RAY DIFFRACTION PHOTOGRAPHS OF ORIENTED SAMPLES

PLATE 1

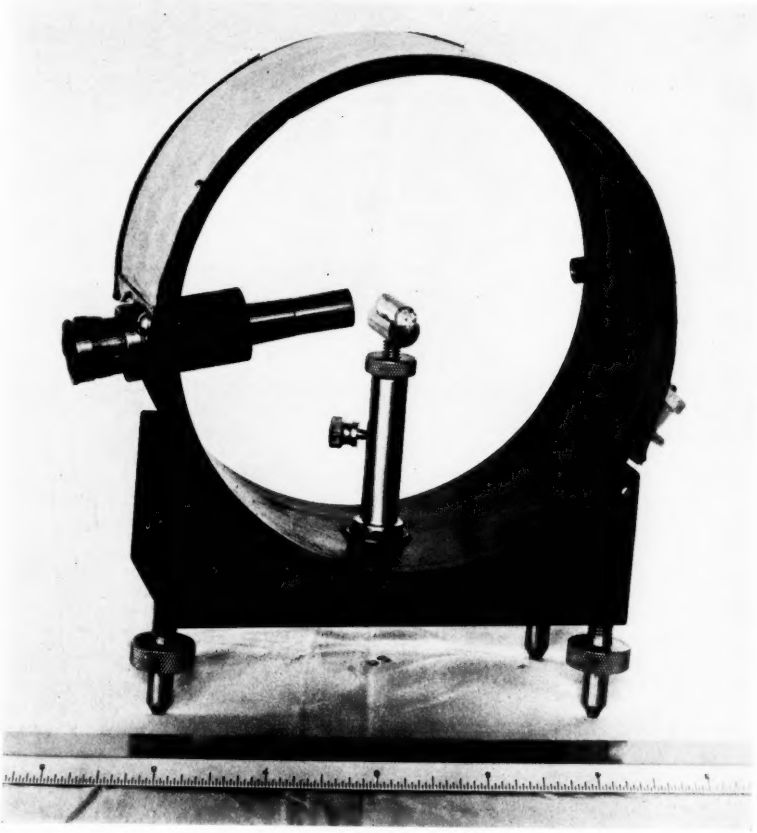
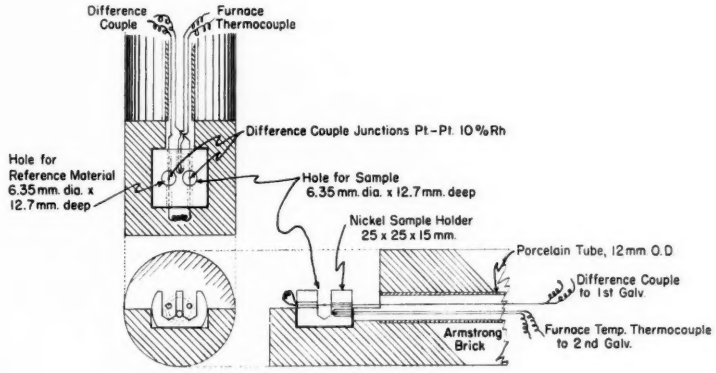
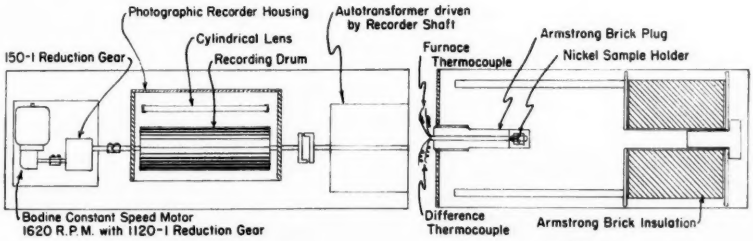


PLATE 2

APPARATUS USED FOR DIFFERENTIAL THERMAL ANALYSIS

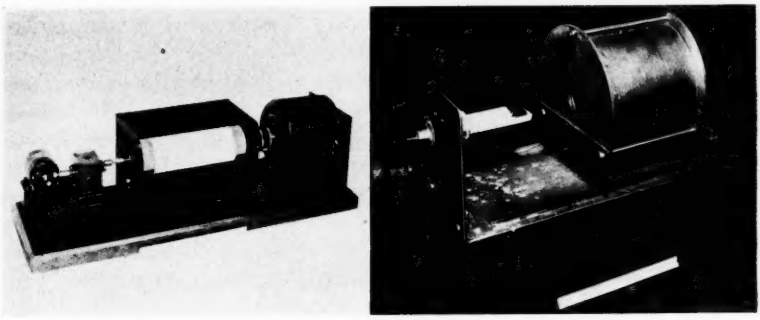

Difference Couple
Furnace Thermocouple
Difference Couple Junctions Pt-Pt. 10%Rh
Hole for Reference Material 6.35mm. dia. x 12.7mm. deep
Hole for Sample 6.35mm. dia. x 12.7mm. deep
Nickel Sample Holder 25 x 25 x 15 mm.
Porcelain Tube, 12mm O.D.
Difference Couple to 1st Galv.
Armstrong Brick
Furnace Temp. Thermocouple to 2nd Galv.

DETAIL OF SAMPLE HOLDER



PHOTOGRAPHIC RECORDER

FURNACE ON TRACK
to slide forward over sample holder



MINERALS PRESENT IN SOIL COLLOIDS: II. ESTIMATION IN SOME REPRESENTATIVE SOILS

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Methods for identifying mineral components of soil colloids described in the previous paper are here applied to a group of colloids separated from some soils of the continental United States. The colloids examined were from soils of five different great groups. These included a number of red podzolic and gray-brown podzolic soils, and a representative of the prairie, chernozem, and desert great groups. In general, the colloid studied was extracted from the B_2 horizon, but several horizons of the Chester and desert soils were examined. Locations, classifications, and natures of parent rocks from which the soils were derived are listed in table 1. References are given in table 1 to sources of fuller descriptions, locations, and analytical data other than those obtained in this work.

Examinations were carried out on material having an effective diameter of less than 0.3 μ, which was separated from aqueous suspensions by a high-speed centrifuge. This fraction usually amounts to about 75 per cent of the material smaller than 2 μ, the quantity of which in the various soils, as determined by mechanical analysis, is listed in table 3.

Chemical analyses useful in identifying minerals of the colloid fraction are given in table 2. Ignition losses at various temperatures and determinations of free and combined Fe_2O_3 were carried out in the course of this work. The remainder of the analyses were taken from the references cited in table 1. Those constituents considered unessential for identifying the principal components of the colloidal fractions are omitted from the table.

Estimates of amounts of various minerals present, based on analytical, x-ray diffraction, and thermal methods, are listed in table 3, together with a composite estimate based on all three methods. The principal components found are some of those described in the preceding paper, specifically, kaolinite, hydrous mica, and free oxides and hydrous oxides of iron.

The best estimate of the amount of iron present as oxides and hydrous oxides is obtained from the chemical analyses. It must be borne in mind, however, that the chemical method for determination of free oxides and hydrous oxides does not differentiate between amorphous and crystalline material. Though

[1] Bureau of Plant Industry.

[2] Bureau of Chemistry and Soils.

TABLE 1

Sources of soil colloids used

SOIL SERIES AND LOCATION	GREAT GROUP	PARENT ROCK	REFERENCE DESCRIBING SOURCE*
Cecil, Iredell Co., N. C.	Red podzolic	Granitic	1
Greenville, Dougherty Co., Ga.	Red podzolic	Coastal plain, interbedded with limestone	2
Decatur, Franklin Co., Ala.	Red podzolic	Limestone	2
Dewey, Franklin Co., Ala.	Red podzolic	Limestone	2
Fullerton, Cherokee Co., Ala.	Yellow podzolic	Cherty limestone	2
Frederick, Rockbridge Co., Va.	Gray-brown podzolic	Limestone	2
Hagerstown, Center Co., Pa.	Gray-brown podzolic	Limestone	2
Hagerstown, Washington Co., Md.	Gray-brown podzolic	Dolomitic limestone	2
Hagerstown, St. Francis Co., Mo.	Gray-brown podzolic	Limestone	2
Chester, Montgomery Co., Md.	Gray-brown podzolic	Granitic	3
Manor, Fairfax Co., Va.	Gray-brown podzolic	Granitic	3
Miami, Grant Co., Ind.	Gray-brown podzolic	Glacial till	1
Carrington, Buchanan Co., Ia.	Prairie	Glacial till	1
Barnes, Grant Co., S. D.	Chernozem	Glacial till	1
Desert soil, Kern Co., Cal.	Desert	Granitic	4

* 1, U. S. Dept. Agr. Tech. Bul. 484; 2, *Ibid* 678; 3, *Ibid* 609; 4, Soil Sci. Soc. Amer. Proc. 3 (1938).

TABLE 2

Chemical analyses of soil colloids

SAMPLE NUMBER	SOIL SERIES	HORIZON	K_2O	MgO	Al_2O_3	Fe_2O_3		SiO_2	H_2O HELD AT	
						Combined	Free		100°C.	300°C.
			per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
C9418	Cecil	C	0.04	0.22	30.5	2.1	15.4	35.1	12.4	9.4
C1067	Greenville	B_2	0.07	0.35	34.6	1.6	10.4	38.8	12.1	10.4
C125	Decatur	B_2	0.88	1.03	31.3	1.5	13.3	39.1	10.9	8.8
C120	Dewey	B_2	0.84	1.00	31.3	1.1	12.7	40.4	10.4	8.6
C109	Fullerton	B_2	1.28	1.07	27.2	1.6	7.7	49.8	9.4	7.4
C810	Frederick	B_2	1.22	1.23	32.6	1.0	10.5	40.3	11.3	9.3
C801	Hagerstown (Pennsylvania)	B_2	1.45	1.34	32.5	1.5	8.9	41.4	11.1	9.2
C805	Hagerstown (Maryland)	B_2	2.30	2.18	30.0	2.0	7.6	43.2	10.4	7.8
C1486	Hagerstown (Missouri)	B_2	1.61	1.62	27.1	3.5	7.0	46.7	9.4	6.7
C1671	Chester	A_2	1.71	1.08	29.5	2.5	10.8	38.6	10.0	7.5
C1672	Chester	B_2	1.58	1.11	27.4	2.6	15.0	39.0	10.9	7.4
C1673	Chester	C	1.44	0.97	27.6	2.5	17.7	36.5	11.1	7.3
C814	Manor	B_2	1.53	0.92	30.3	2.6	10.1	40.3	10.6	7.8
C10343	Miami	B_2	4.37	2.09	23.4	4.4	7.1	47.1	7.8	4.7
C10086	Carrington	B_2	1.85	1.81	24.3	4.0	9.7	45.4	9.6	6.4
C10307	Barnes	B_2	1.44	2.68	19.4	9.8	0.0	49.2	7.2	5.6
C3420	Desert soil*	B_1	1.99	2.91	25.4	7.6	2.8	47.5	8.9	7.0
C3421	Desert soil*	B_2	1.67	2.97	24.2	8.9	2.2	48.0	8.9	6.7
C3422	Desert soil*	B_3	0.87	3.30	22.5	8.4	2.4	49.5	8.9	6.4
C3423	Desert soil*	C	0.70	3.41	22.0	7.7	2.0	50.1	8.8	6.4

* This soil has not yet been correlated but is very similar to soils of the desert group, except that it is formed from residual granitic material instead of transported.

the x-ray method gives some evidence of the nature of the iron oxide, it cannot be used as the basis for an estimate, and thus does not eliminate the possible

TABLE 3

Estimates of mineral components of soil colloids

SAMPLE NUMBER	SOIL SERIES	ANALYTICAL		X-RAY				THERMAL ANALYSIS, KAOLIN	COMPOSITE ESTIMATES*					CLAY (2μ) BY MECHANICAL ANALYSIS
		Hydrous mica	Free iron oxides	Kaolin	Hydrous mica	Montmorillonite	Cryst. iron oxides		Kaolin	Hydrous mica	Montmorillonite	Free iron oxides	Quartz and calcite†	
		per cent	*per cent*	*per cent*	*per cent*	*per cent*		*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
C9418	Cecil	Abs.	15	80	Abs.	Abs.	G.H.‡	80	80	0	0	15		44
C1067	Greenville	Abs.	10	80	Abs.	Abs.	G.H.	90	90	0	0	10		42
C125	Decatur	>10	13	80	10	Abs.	G.H.	50	70	10	0	13		49
C120	Dewey	>10	13	80	10	Abs.	G.H.	60	70	10	0	13		36
C109	Fullerton	>25	8	70	30	Abs.	G.	70	60	20	0	8	10 quartz	49
C810	Frederick	>25	10	70	20	Abs.	G.	70	70	20	0	10		70
C801	Hagerstown (Pennsylvania)	>25	9	70	20	Abs.	G.H.	70	70	20	0	9		55
C805	Hagerstown (Maryland)	>50	8	50	50	Abs.	G.H.	50	50	40	0	8		70
C1486	Hagerstown (Missouri)	>25	7	50	50	Abs.	G.	40	40	40	0	7	5 quartz	39
C1671	Chester	>25	11	60	30	Abs.	G.H.	40	50	30	0	11		20
C1672	Chester	>25	15	60	30	Abs.	G.H.	40	50	30	0	15		25
C1673	Chester	>25	18	60	30	Abs.	G.H.	40	50	30	0	18		17
C814	Manor	>25	10	60	30	Abs.	G.H.	50	50	40	0	10		24
C10343	Miami	>75	7	10	80	...	....	10	10	80	0	7		51
C10086	Carrington	>25	10	50	30	10	‖	30	40	40	10	10		24
C10307	Barnes	>25	0	30	40	20	....	20	30	40	20	0	6 calcite	36
C3420	Desert soil	>50	3	20	80§		....	20	20	70§		3		36
C3421	Desert soil	>25	2	20	80§		....	20	20	70§		2		35
C3422	Desert soil	>10	2	20	80§		....	20	20	70§		2		30
C3423	Desert soil	>10	2	20	80§		....	20	20	70§		2		14

* The authors have made no attempt to make these add to exactly 100, since the values are inexact.

† Amounts of quartz were estimated from the x-ray diffraction patterns; and calcite, from chemical analyses. Quartz present in amounts less than 5 per cent is not indicated because of uncertainty of identification.

‡ G. and H. indicate the presence but not the amounts of goethite and hematite respectively.

‖ Some unknown iron-bearing component, about 10 per cent.

§ The principal mineral present in these soil colloids is of the mixed layer type.

presence of amorphous material. Actually, both goethite and hematite were identified from the x-ray diffraction patterns, as indicated in table 3.

In some colloids free hydrous oxides of iron are indicated by thermal analysis, as illustrated in figure 1, but the method does not appear trustworthy for estimating their amounts. In fact, the temperatures at which such hydrous materials in the colloids lose their water of composition seem to be very variable over the region 275–375°C. Moreover, the endothermic effect is not so great as would be expected from the probable amounts of goethite present. Thermal analysis of the colloid from the Cecil soil indicated the presence of a small amount of goethite even after the usual treatment for removing free oxides and

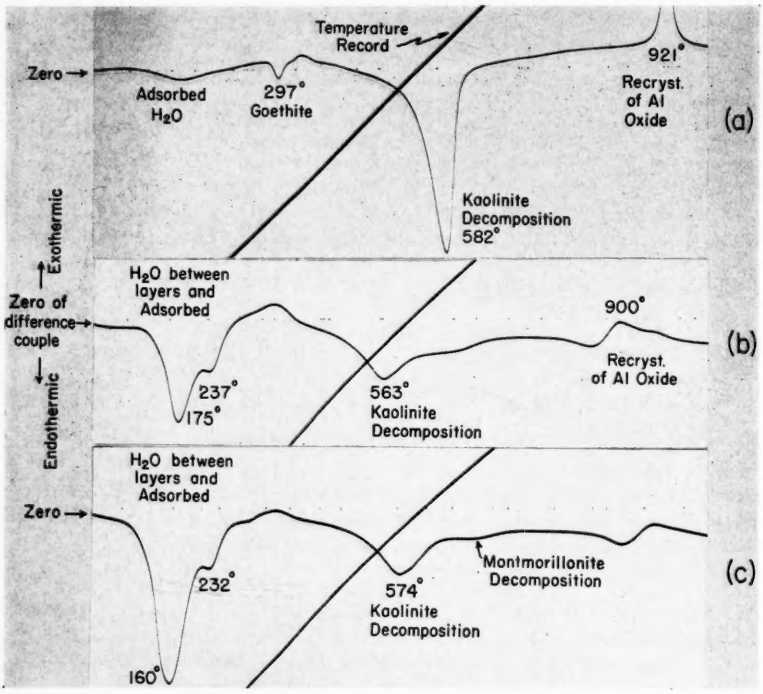

FIG. 1. DIFFERENTIAL THERMAL ANALYSIS CURVES FOR (*a*) CECIL, (*b*) DESERT, AND (*c*) BARNES SOIL COLLOIDS

hydrous oxides of iron. For this reason the amounts of combined iron indicated in table 2 include any small amounts of undissolved oxides.

The amount of K_2O obtained by chemical analysis is a good criterion for estimating the minimum quantity of hydrous mica, as this is the only mineral present that contains potassium. In making the estimate in the third column of table 3, it was assumed that hydrous mica contains 5 per cent K_2O. This estimate is considered to be a minimum one because hydrous mica present in the various colloids might contain less than 5 per cent K_2O but probably

not more than that amount. It was pointed out in the preceding paper that the amounts of magnesium, combined iron, and water loss at various temperatures give a method for rough qualitative identification of hydrous mica and montmorillonite, and this can be seen by inspection of tables 2 and 3.

Estimates of kaolinite, hydrous mica, and montmorillonite, determined by x-ray diffraction from oriented samples, are listed in table 3. Such estimates are quite approximate, as they are based upon visual comparison of intensities. They depend, moreover, upon the various minerals orienting without preference, which seems to be the case in samples free of organic matter and of free oxides and hydrous oxides of iron. The x-ray method gives a more absolute value for estimating the amounts of hydrous mica present than does the chemical analysis. In general, however, the minimum amount of hydrous mica indicated by the chemical analyses is in agreement with the amount as estimated from x-ray diffraction patterns.

Montmorillonite was identified only in the colloids from the Barnes soil and possibly the Carrington soil. The predominent constituent of the colloids separated from the desert soil can best be described as a mixed layer mineral of the type discussed in the preceding paper. In these colloids the mixed layer mineral is probably composed of montmorillonite and hydrous mica layers. The coarser fractions of the soil contain a mineral that is essentially identical, except for particle size, with that of the colloid.[3]

The amount of kaolinite present in a sample can best be determined by thermal analysis. Agreement with estimates based on x-ray diffraction are not so close as might be desired, but both methods are subject to considerable refinement if necessary. As different samples varied greatly in apparent densities, it was necessary to vary the weight used for thermal analysis, since the volume was maintained constant. The method was standardized against pure kaolinite.

Differential heating curves obtained from the Cecil, desert, and Barnes soil colloids are shown in figure 1, and some features of interest are indicated. These curves can be compared with those of clay minerals by referring to the preceding paper. The endothermic change accompanying decomposition of kaolinite near 580°C. is apparent for each soil colloid. The area of this endothermic region was used in estimating the amount of kaolinite, and it perhaps is evident that measurement of the area could not be very accurate, particularly where the amount of kaolinite is small.

X-ray diffraction patterns indicate the presence of quartz in a number of the samples, the greatest amount being in the colloid separated from the Fullerton soil, which contained about 10 per cent. The Hagerstown (Missouri) soil colloid contained about 5 per cent quartz, and the remainder of the samples less than this amount. Small quantities of quartz cannot be identified with

[3] Drosdoff, M., and Miles, E. F. 1938 Action of hydrogen peroxide on weathered mica. *Soil Sci.* 46: 391–396.

certainty in the presence of considerable hydrous mica, because the strongest diffraction line of the former is very close to a moderately intense line of the latter. As mentioned in the preceding work, the amount of quartz present in some samples depends, in a large measure, on the upper size limit chosen in separating the colloid. Its presence in considerable quantities vitiates any use of SiO_2:(R_2O_3 + RO) ratios in drawing conclusions about the nature of clay minerals present.

X-ray diffraction patterns of the colloid separated from the Carrington soil showed a minor component that could not be identified with certainty. It was removed by the treatment given in the determination of the free iron oxides and thus supposedly is a compound rich in iron. The possibility of this unknown component's being goethite could not be eliminated with certainty. As a matter of fact, the diffraction pattern of goethite does not contain lines of sufficient intensities to permit the ready identification of this mineral in mixtures in which it is a minor component.

Chemical analyses of the colloid separated from the Barnes soil showed that it contained about 6 per cent calcium carbonate. X-ray diffraction patterns of this untreated soil colloid, which contained about 2 per cent organic matter, were poor, and gave a meager, but positive, evidence for the presence of calcite. The chemical method, of course, is the best one for estimating calcium carbonate.

DISCUSSION

The properties of the inorganic colloidal fraction of soils are necessarily determined by the characteristics and amounts of the component minerals. Attempts to identify and to estimate these minerals have been based chiefly upon chemical analysis. With the background of mineralogical information now available, which was briefly outlined in the preceding paper, the significant analyses for mineral identification are evident.

Tables 2 and 3 show that potassium is present in considerable amounts only when hydrous mica is one of the components. The Cecil and Greenville colloids, both of which contain less than 0.1 per cent K_2O, contain no detectable amounts of hydrous mica. On the other hand, the Miami colloid, which is largely hydrous mica, contains the greatest amount of potassium, 4.4 per cent K_2O. A similar but less striking relationship is indicated by the amount of combined Fe_2O_3 and MgO, as well as by the H_2O held at 300°C. This temperature was selected as being sufficiently high to drive off adsorbed water and the swelling water of montmorillonite, but not so high as to cause much decomposition of the kaolinite.

Attention has been directed to the caution that must be exercised in the use of SiO_2:(R_2O_3 + RO) ratios for identifying clay minerals. An excellent illustration is afforded by the data given in table 2 for the Carrington and Miami colloids. The SiO_2:(Al_2O_3 + combined Fe_2O_3 + $\frac{2}{3}$ MgO) ratios of these colloids are 2.6 and 2.7, respectively, though their mineralogical com-

positions are very different, the former containing about 40 per cent kaolinite and 40 per cent hydrous mica, the latter about 10 per cent kaolinite and 80 per cent hydrous mica. These differences are correctly indicated by the potassium content and the amount of water held at 300°.

The most serious limitation of chemical data is that they do not permit quantitative estimations and will not detect the presence of minor amounts of kaolinite. Thermal analysis supplements the chemical information, in that it gives the best basis for determining the amount of kaolinite. Use of these two methods gives a fairly satisfactory basis for estimating the component minerals of a soil colloid.

X-ray diffraction data, of course, have served as the basis for the entire development and give a method for estimating all of the components save the free oxides and hydrous oxides of iron. Estimates by the various methods are in essential agreement. The values listed in table 3 have been rounded off so as to indicate their probable accuracies.

The number of samples examined in this work is not sufficiently extensive to warrant general discussion of the relationships between mineral composition of a colloidal fraction and classification of a soil. Results obtained, however, indicate prominent differences between colloids from the B horizons of some different soil groups. Data presented in table 3 suggest that red podzolic soil colloids contain kaolinite as the predominant components, accompanied by large amounts of hydrous oxides and free oxides of iron. Very red soils owe their color to the presence of hematite, as is well illustrated by the Decatur. Gray-brown podzolic soil colloids contain both kaolinite and hydrous mica as prominent components, accompanied by appreciable amounts of free oxides and hydrous oxides of iron.

SUMMARY

Minerals present in the colloidal fraction of 15 soils from continental United States have been identified and their amounts estimated by use of the chemical, thermal, and x-ray diffraction methods discussed in the preceding paper. Kaolinite and free oxides and hydrous oxides of iron were the predominant components of the red podzolic soils examined. Gray-brown podzolic soil colloids contained these minerals associated with appreciable amounts of hydrous mica. Single examples of colloids separated from soils of the chernozem, prairie, and desert group groups were studied.